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REFERENCE

Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 35c.)

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CONTRIBUTION TO A GENERAL THEORY OF MEANDERING VALLEYS

G. H. DURY

ABSTRACT. Systematic valley windings have often been taken as homologues of river meanders, and ascribed to erosion by powerful ancestral streams. River capture and the decay of ice- or snowfields are among the agencies variously credited with the implied reduction of discharge. Alternatively, the windings have been referred to peculiarities of rocks or structure. None of the several hypotheses explains the wide distribution of winding valleys, or their development on a regional scale.

Recent experiment and observation indicate that meandering can be wholly independent of external obstacles, and that the size of the loops is closely related to discharge. Furthermore, the alluvium in a number of winding valleys is shown, for the first time, to occupy large channels which meander, with appropriate bed form, round the valley bends. It is therefore concluded that the bends were in fact cut by streams, which were larger than those which now flow.

The discharge of the large channels at bankfull stage can be approximately determined from well-known formulae. It is found that present-day precipitation, however much the runoff might be concentrated in a single season, would be inadequate to supply discharges of the required order. Formulae for flood discharge are used to indicate the rates of rainfall per hour capable of nourishing the large former streams.

Although much work remains to be done on problems of dating, it appears likely that the high rates of rainfall and the resulting high river discharges obtained at various times during the Pleistocene. Certain implications concerning processes and modes of landscape evolution in the areas affected call for detailed investigation.

INTRODUCTION

The problem discussed in this paper is that of the combination of river meanders with equally systematic but far more ample windings of the valleys in which the river flows. In certain parts of the world such a combination is widely observed. It has naturally stimulated enquiry from time to time, mainly on the part of physical geographers, but as yet no single explanation has been exclusively accepted.

Logical reasoning about the problem is hampered by the nature of the terms in current use, for these are not merely descriptive but also embody genetic implications, as if the questions at issue had already been resolved. Thus the expression *meandering valley* is applied where the pattern of valley windings broadly resembles the trace of a meandering stream and where successive windings are for the most part of the same general order of size. Similarly a *valley meander* is an individual member of the series of windings. Now it is evident that each of these terms can be taken to imply that valley windings of the kind in question are homologous to river meanders, the difference being merely one of size. Many works indeed contain the tacit assumption that the two groups of features have originated in identical fashion. On the basis of evidence and reasoning which are presented later in this account, the writer considers homology to be in fact proved, but until

the data have been considered it is proposed to use the noncommittal descriptive terms *winding valley* and *valley bend*. The assumption of homology is also implicit in the expression *underfit stream* (often also called *misfit stream*), by which is meant a stream too small for the valley in which it flows. It is quite clear that Davis, to whom these two terms are due, did not intend to suggest that for a given size of stream there is an appropriate size of valley, but only that certain valleys show signs of having been cut by streams far larger than those which now flow in them. The evidence adduced by Davis as indicating an underfit condition consists precisely of the combination of valley windings and river meanders. His interpretation has prevailed to the extent that underfit stream has passed into the literature as connoting a stream meandering within the limits of the bottom of a winding valley.

A second assumpion on which the use of the term underfit must depend, and which is also implicit in Davis' interpretation of valley bends, is that the dimensions of meanders are related to amount of stream discharge. Here is the deductive basis—as opposed to induction from the analysis of landform—of the inference that valley windings were shaped by rivers far more powerful than the rivers now observed, and that streams described as underfit have at some time been greatly reduced in volume. None of the geographers and geologists who alone seem to have considered the problem of valley windings appears to have checked or tested this second assumption, where it has been implied. Clearly, however, it is the essential premise to a certain line of reasoning, and as will be seen, supports a whole group of hypotheses. Its unquestioning acceptance (mainly by writers in English) may be unfortunate but is not altogether surprising; for the critical data must come from physical and mathematical investigations of the general problem of meandering currents. This work is still in its early stages, and the necessary information is only now becoming available. At the same time, it is of first importance to recognize the assumption for what it is, in order to evaluate the worth, force, and validity of the views summarized in the next section, and to understand how an authoritative group of writers could commence with very different postulates.

As with valley meander, the debatable term underfit will be avoided as far as possible in the discussion which follows.

PREVIOUS HYPOTHESES

Existing hypotheses of the origin of winding valleys fall into two groups: those which require stream discharges formerly higher than the present, and those which do not. The first group is summarized in the first four sections below, the second in the fifth. The summary is followed in the next section by a statement of the need for a general hypothesis, together with reasons for rejecting the hypotheses listed here.

The capture hypothesis.—This is the principal hypothesis of the group where changes in stream discharge are assumed or inferred. It was formulated by W. M. Davis (1895, 1896, 1899) with reference to valley features in the Cotswold Hills of England, the scarplands of the Paris Basin and Lorraine, and the South German Scarplands. In all these areas, boldly winding valleys containing small meandering streams occur on the dip slopes of

strong geological formations. Davis quite properly identified the spurs between successive valley bends as similar in form to the meander lobes of many incised meandering rivers; for the spurs are often trimmed on the upstream side, as if by a large river, while at the extremity of valley bends the outer valley side is frequently very steep, in marked contrast to the gentle descent opposite (fig. 1). If, then, valley bends were the work of former great streams, the problem became merely one of accounting for the loss of water. The mechanism seemed ready to hand in the river capture to be expected in landscapes of this kind. Davis was at the time concerned with elaborating the

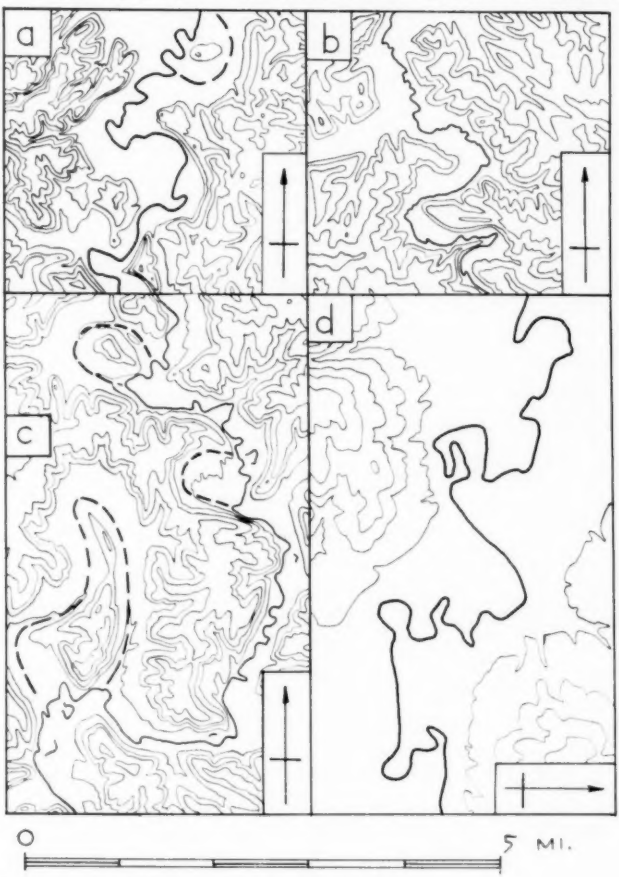


Fig. 1. Examples of winding valleys in the U. S. A.
a, Tygarts Creek, Kentucky (Greenup Quadrangle);
b, Fennimore Fork, Wisconsin (Boscobel Quadrangle);
c, Kickapoo River, Wisconsin (Wauzeka Quadrangle);
d, Tualatin River, Oregon (Tualatin Quadrangle);
Contour interval throughout, 100 ft. Pecked lines indicate abandoned valley bends. Tributary streams omitted for clarity.
Based on the maps of the U. S. Geological Survey.

scheme of the normal cycle of erosion and with presenting it in Europe. The uniclinal structure of scarpland country is especially well adapted for reference in discussing the evolution of drainage systems, and the river capture which is likely to occur frequently in the course of the normal cycle; many of the dip streams of the scarplands mentioned do, indeed, head in or near gaps in the scarp crest, and there is every reason to conclude that they have been beheaded by more successful competitors working along the weaker outcrops. It was an obvious step to conclude that the valley windings were cut before capture occurred, at a time when more extensive headwaters provided a greater flow.

In this conclusion Davis was followed by S. S. Buckman (1899, 1902) and later by many others. His own observations of anomalous facts, and his later expressions of a limited dissatisfaction with the simple capture hypothesis have, on the other hand, attracted little attention. In the three early papers cited, he noted that near the Cotswolds the Avon, supposedly a leading captor stream, also describes small meanders within a winding valley, and has, therefore, also presumably suffered a loss of flow, whereas it should have gained in volume to the extent that the beheaded dip streams lost. In the Swabian Alb also, a dip stream classed as underfit seems not to have been beheaded. In the classic instance of the capture of the upper Moselle from the Meuse, the latter seems too small for its valley both above as well as below the point of capture, for valley windings and river meanders occur in both reaches alike. Davis was impelled to postulate in addition to capture a loss of water doubtless due to "some climatic change of external and obscure origin." The main hypothesis still stood, however, and he restated it in 1923, apparently with approval.

Hypothesis of overspill of glacial meltwater.—Davis reopened the question of winding valleys in the Cotswolds after an interval of ten years (Davis, 1909), suggesting that small ice-dammed lakes might have discharged through the cols to provide powerful streams in the valleys of the dip slope. A similar view appears in Arkell's detailed studies of the same piece of country (1947a, 1947b). A variant opinion is that glacial meltwater or snowmelt, without the intervention of a lake, formerly provided high discharges.

Hypothesis of underflow.—In a paper of 1913 Davis admitted the inadequacy of river capture as a general explanation of stream shrinkage but was little inclined to substitute climatic change. He suggested that water might be lost to deep percolation and to shallow underflow through alluvium. As is well known, his views on graded waste slopes and the wastage of divides logically demand some infilling of trunk valleys during the mature stage of the cycle; this aggradation seemed capable of promoting powerful underflow.

Hypothesis of erosion by floodwater.—Certain writers (Engelmann, 1922; Flohn, 1935) have thought that rivers in flood might be capable of eroding valley bends. This view refers to former as well as to contemporary floods, and is related to the postulate of snowmelt already mentioned.

Structural hypotheses.—Under this head come those interpretations of valley windings which depend on the supposed influence on a downcutting meandering river of lithology, lithological succession, attitude of strata, or

earth movements. French and German writers have been especially prominent in this connection. Thus Vacher (1909) considered that a river cutting in weak rock would, on encountering more resistant strata, develop more ample curves. A diametrically opposite view appears in Blache (1939, 1940) who regards small meanders (sc. river meanders) as a response to weaker rock in the valley bottoms. Musset (1928) identified more than one "generation of meanders" on the Loire, separating them in time by episodes of downcutting and slope reduction whereby he thought to account for the smaller amplitudes of the later curves. Cole (1930) related river meanders to the structure of the bedrock. Masuch (1935) also noted some relation between rock structure and the enlargement of meanders during downcutting (ingrowth of meanders), but considered valley windings characteristic of antecedence and superimposition rather than a response to structure. For reasons which the present writer does not find convincing, she did not regard as essential a genetic connection between river meanders and valley windings [talmaänder]. A useful survey of earlier work appears in Flohn (1935) who, while rejecting structural hypotheses and favoring flood flow as a cause of valley bends, concluded that these features are morphological convergences which can originate in different ways.

Miscellaneous hypotheses: The question of inheritance.—Wright (1942) ascribed valley bends to the fact that the loops of an incised stream are unlikely to suffer cut-off, with the result that they undergo progressive enlargement: this is the concept of "auto-underfitness." Bates (1939) thought that the development of river meanders is a response to aggradation, and Baulig (1925) had previously maintained that underfitting is a proof of aggradation in progress. It should be noted that Baulig later modified his opinion, stating in a more detailed study (1948) that the present condition of rivers is abnormal, and postulating a formerly much greater flow simultaneously reduced throughout the length of a stream. Nevertheless he was unwilling to accept climatic change as the basic cause, on the ground that such change should make all the rivers of a vast region underfit, and appealed to steepened slopes in the lower courses as a means of provoking more powerful currents.

The debate on winding valleys has been complicated from time to time by confusion between river meanders and valley bends, and by contradictory views on whether or not valley bends are necessarily inherited from a previous cycle of erosion. The question of inheritance is relevant not only to the problem of origin but also to the matter of dating.

Lehmann (1915), although reluctant to lay down a fixed rule, thought incised meanders unlikely to develop in a single cycle. With Flohn and Hol, he is among the critics of Davis' well-known scheme of the evolution of an incised meandering stream. Lehmann wished to take into account the wide range of variation found in nature, for example, in the relation of valley side to valley floor. Hol (1938, 1939), commencing by a penetrating critique of earlier work, concluded that all true incised meanders result from two cycles of development. The opposite view appears in Blache (1939, 1940), who identifies a valley bend on the Moselle as having originated in the present cycle, and also in Baulig (1948).

THE NEED FOR A GENERAL HYPOTHESIS

Not all the hypotheses referred to above can be valid for they are contradictory among themselves. A leading objection to most is that they demand special circumstances, such as local or regional particularities of structure, the incidence of river capture, or the former presence of glacial lakes or of snowfields. It seems highly unlikely on general grounds that any of these can account for the widespread occurrence of winding valleys in country which is lithologically and tectonically varied, and within as well as outside the former limits of ice.

When large areas are inspected in the field, or on large-scale maps and air photographs, valley bends are seen to be as common on captor streams

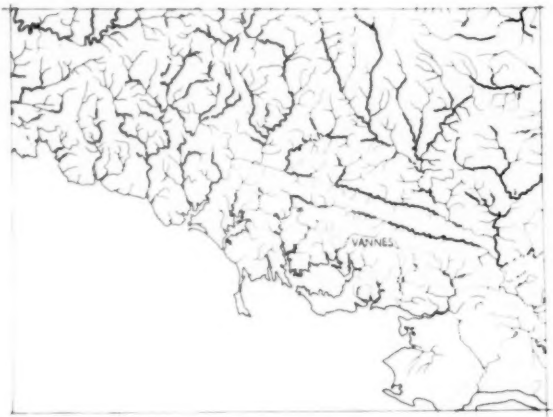


Fig. 2. The drainage net of part of Brittany, showing underfit streams (heavy lines). The map represents an area approximately 80 x 100 miles.

as on those which have been beheaded. The ratio of dimension between valley bends and river meanders is known to be comparable on opposite sides of certain watersheds, even when one group of streams is gaining and the other losing ground (Dury, 1951). A map of the distribution of winding valleys in France, part of which is reproduced here as figure 2, leaves no doubt that they are in fact regionally developed despite Baulig's statement to the contrary. The fact that some valleys are without valley bends is no more surprising than the absence of meanders from certain rivers. Moreover, allowance must be made for the suppression of river meanders in those parts of incised winding valleys where there is simply not room in the valley bottom for them to develop, with the result that the only trace shown on the map is that of the valley bends.

The classic instance of the Toul capture, where the Meuse has lost the upper Moselle (Davis, 1896), has probably served more than any other to support the view that valley bends are the former meanders of streams now diminished by beheading. But the disproportion between valley bends and river meanders on the Meuse is the same both above and below the point of capture, and the capturing Moselle shows similar inferential evidence of

shrinkage. Thus the undoubted occurrence of capture may well have no connection with the problem of a general diminution of stream flow. Now de Martonne (1935, p. 598) has shown that since the capture the Moselle has had time to cut down some 40 meters, developing a valley bend in the process (Blache, 1939, 1940). Any shrinkage of the Moselle has taken place since the cutting of the valley bend, which in turn postdates the capture.

Many other instances of the supposed effect of capture can be disposed of by similar appeals to the elements of simple chronology. It can readily be shown that the gaps at the heads of some streams in the Cotswolds and neighboring hills already existed before the onset of the last local ice, and that the scarp face had already retreated almost to its present position by that time. All but the last minor reductions in the length of the dip streams had already taken place. But as will be shown later, the valley bends were still being eroded after the ice had disappeared. The most convincing single illustration that valley windings are not related to river capture is provided by the Stratford Avon, which is known not to have suffered capture since its initiation on a great spread of drift (Shotton, 1953). Any reduction in the discharge of this river must clearly have occured independently of capture, and also late in the day; for the forms of the valley leave no doubt that the valley bends continued to evolve, at least from time to time, until the river had cut down to its present level.

Postulates of discharge from temporary ice-dammed lakes or from the ice front are readily seen to be irrelevant to the general problem of winding valleys, when it is observed that these can occur well outside the extreme limits of Pleistocene glaciation. This fact appears strikingly on the map of France mentioned above and is also evident in the English Weald, where streams were selected for detailed study. In the broad view, too, it is difficult to imagine a system of lakes or glaciers which could have provided large rivers in all the winding valleys known to occur within the area formerly ice-covered.

The supposed efficacy of underflow through alluvium has been strongly criticized, for instance, by Wright (1942) and Baulig (1948). The process is not usually considered very seriously nowadays, but it may be noted in passing that if valley bends were cut by large streams the reduction of discharge far exceeds anything that underflow could explain. It is pertinent to remark here that certain winding valleys, including some of those described in a later section, are cut in impermeable bedrock and lined with fine-grained alluvium. In these cases, not only can underflow through the alluvium be disregarded but also it is obvious that losses to deep percolation are nil or negligible.

Erosion of valley bends by floodwater in the present climatic regime can also be readily dismissed. It is a matter of observation that "normal" floods (using the term in the hydrological sense) fail to erode the sides of most meandering valleys or to disturb all the alluvium of the valley floor. The spreading of floodwater over a floodplain is well known to reduce the peak flow; but erosion of valley bends can scarcely begin until the mode of flow over the floodplain is comparable to the violent motion which occurs in the

main channel. Presumably there is for each valley a critical depth of water at which the floodplain alluvium would begin to move bodily, but this depth is not attained in present conditions even with exceptional floods. Probability analysis provides exactly the information required in calculations of the height of the centennial flood, the greatest flood to be expected in a randomly selected 100-year period—Pickels (1937) showed that for streams in Illinois the centennial flood is only of the order of two to three times the mean flood. More recently, it has been calculated that the exceptional floods of spring 1947 on the Northamptonshire Nene reached or even exceeded the level of the centennial flood (Crocker, 1952), while on the Severn the centennial level was closely approached in the same year (Rhodes, 1952). It appears safe to conclude that even the highest flood discharges now experienced are inadequate to account for the erosion of valley bends.

Although incised winding valleys are commonly associated with resistant rock, it is a mistake to suppose that the association has the force of a rule, as is usually done by those who seek the origin of valley bends in some response to lithology or structure. The only necessary connection seems to be the ability of strong rock to develop, sustain, and preserve steep slopes. Moreover, valley bends are not entirely confined to resistant outcrops or to incised reaches. The Stratford Avon has already been mentioned as having been initiated upon drift, in which it developed and incised a series of well-formed valley bends. One of its tributaries, the Warwickshire Itchen, has cut a winding valley through the moderately resistant outcrop of a limestone-shale series, but also describes valley bends as well as river meanders in the flat strike vale carved from the weak overlying clays. In the Weald of southeastern England, valley bends are numerous on the Weald Clay, a formation noted for its low resistance to denudation. Observations of this kind suggest that the low frequency of valley bends on weak rocks may be due to the tendency for the wide valley floors to be even and formless, and to the speed with which changes in the stream are reflected here in changes in the whole landscape.

The various special cases of the possible influence of structure or earth movements which certain writers have discussed again fail to carry conviction in view of the presence of winding valleys in homogeneous as well as in heterogeneous rock, in horizontal as well as in folded strata, and on weak as well as on strong outcrops. Since many of the valleys occur in tectonically stable areas, it must be concluded that local earth movements have no necessary bearing on the problem of their origin.

Attempts to explain valley bends as river meanders enlarged in especially favorable circumstances must also be regarded with doubt. Some workers seem to have overlooked the fundamental distinction between windings of two orders of size, perhaps because of the suppression—mentioned above—of river meanders in some confined reaches of winding valleys. The tendency of many rivers to enlarge their loops during incision is widely recognized but should not be permitted to obscure the fact that valley bends are usually very much more ample than the curves of the river. It is also necessary to bear in mind the possibility that stream discharge and dimension of meanders may be related. The final, and definitive, objection to the interpretation of valley bends

as hypertrophied incised meanders is, however, provided by the evidence described in a later section that some winding valleys can be proved to contain filled stream channels much larger than those in use at the present time. Thus, there can be no doubt that two sets of features are in question.

Aggradation in progress cannot be accepted as a cause of small-scale winding unless it can be demonstrated. But as far as investigation of selected cases shows, mean down-valley gradient has changed very little since the present river meanders came into being, and in one instance at least excavation not infilling can be shown to be going on. Thus, although diminution of stream discharge should lead to valley filling (other things being equal), both should be looked on as the effects of a common cause.

The view that valley windings are necessarily inherited from free meanders at a higher level implies that they are not genetically related to outcrops of resistant rock, except of course to the extent that rock resistance has promoted their lateral enlargement during incision. But if inheritance has occurred, it follows (as pointed out by Hol) that the interval between the valley bends was determined before incision commenced. It is also implicit here that the valley bends originated as stream meanders. Since very many valley bends have in fact undergone lateral enlargement—have become *ingrown*[1]—it might be thought that earlier and less sinuous traces could be reconstructed for the higher levels, in order to show if a straight course existed when incision began. In practice the matter is very difficult, and inferential evidence must be relied on. The writer accepts the evidence of Blache (1939, 1940) that the Moselle has cut a valley bend in the course of a single cycle, and has himself recorded the development of meanders in a small gully, *pari passu* with incision (1951). It is concluded therefore that although many series of valley bends may well have originated in the incision of free meanders, inheritance is not essential. Consequently it is not permissible to date the initiation of every incised series to a time before their incision.

For all these reasons, it seems desirable to treat the general problem of valley bends as distinct from the specific problems of external influences on a given stream and to look for agencies which can operate independently of local circumstances. If it can be shown that the size of stream meanders is related to the size of stream, and if convincing evidence can be produced that valley bends are truly homologous to stream meanders, there is a strong case for concluding that in certain areas stream discharge was once higher than it is now, and that a general diminution has occurred. The best method of approach seems to be through a summary of recent views on the cause of meandering, which will serve to indicate the form of a meandering channel and to suggest that a mathematical relation between stream size and meander size actually exists.

RIVER MEANDERS: BED FORM AND SILT TRANSPORT

The mode of flow round bends has attracted the attention of physical scientists for a good many years, and considerable progress has been made in theoretical and experimental research. Physiographers, however, have tended as a group to accept the occurrence of meanders on natural streams

[1] The term is due to Rich (1914).

and to rest content with the postulates that helicoidal flow occurs at bends and that meanders are generated by solid obstacles in the bed. In consequence, much information has been overlooked that is of great use in the interpretation of winding valleys.

As is well known, the bed of a meandering stream is characterized by deeps or *swales* below the outer banks of curves, by shallows or *crossings* at the inflections between successive loops, and by constructional *scrolls* at the inner curved bank. Thus a meandering channel is typically asymmetrical in cross-profile. This description holds good whether the stream is incised or not.

The typical bed form has often been ascribed to or associated with the helicoidal flow which is supposed to take place at bends. The water surface is said to be superlevated at the outside of the curve, so that secondary descending currents are set up near the outer bank and are continued by transverse flow across the bottom towards the inner bank. This interpretation long seemed to account satisfactorily for the channel form, the formation of scrolls, and the lateral enlargement of bends, as well as to explain how meanders could originate in the deflection of the stream: it appears widely in geographical literature. There are, however, serious objections to it. Experiments on natural and on laboratory streams have shown that where bank erosion occurs little material is carried from one side of the channel to the other; instead, it is carried downstream and deposited *on the same side as the eroded bank*. Some authorities maintain that observable secondary flow may be described in terms of a complex of helices rather than of filaments. Moreover, experiments with dyed material and with injected dyes suggest that bed-load movement is not necessarily parallel to flow lines.[2] Leighly in particular has stressed the importance of taking turbulence into account. He finds by analyzing the distribution of eddy conductivity that in an unsymmetrical channel the concentration of force on the deeper parts of the bed is disproportionately large in comparison to the depth of water. Also he holds that maximum turbidity should occur at the bottom of the swale, with deposition lateral to some thread of maximum velocity and its flanking threads of maximum turbulence. On these grounds it is easy to suppose that mere asymmetry of the channel could account for the lateral enlargement of a bend, without appeal to centrifugal force. Once a bend and the associated deep were in being, turbulent transfer of material towards the inner bank would occur, until some kind of equilibrium was achieved between the forces tending to move material towards the inner bank and the gravitational pull towards the bottom of the swale.

As will appear, an interpretation of this kind accords with the results of recent work on the initiation of meanders. It will be noted that the forces at work are thought of as operating generally throughout the stream. This in itself opposes the view that meanders are due to external obstacles, but a few additional points may be noted in passing. As Hjulström (1942, 1949) remarks, meandering is usually least developed precisely where natural streams

[2] It will be realized that this review is presented in the most summary form. It has been necessary to refer to the results, without discussing the evidence, of the following authors: Blue et al. (1934), Claxton (1927), Eakin (1935), Einstein (1926), Friedkin (1945), Leighly (1932, 1934), Matthes (1941), Quraishy (1942), Russell (1936), Tiffany and Nelson (1939), Vogel and Thompson (1933).

are most easily deflected and where obstacles are most numerous, that is, near the sources. The truth seems to be that obstacles impede the initiation, development, and propagation of meanders; supporting evidence comes from the experiments of Friedkin, and from the field observations of Russell (1936), Matthes (1941), Fisk (1944), and Strahler (1946).

In this connection also, it may be stated that geographical (and other) literature contains many references to the supposed influence of gradient in the initiation or modification of meanders. Some hold that meandering increases the length of a stream, so that energy is reduced by the lessening of gradient and dissipated by the attack on the banks. A grave weakness in this argument is that it seems to impute finality to the stream; it has been used, however, in attempted explanations of the ample curves of valley bends. The opposite opinion is also to be found, that meandering occurs only on slight gradients: the stream is held to be easily deflected because of its low velocity. Thus meanders are rather remarkably ascribed either to an excess or to a deficit of stream energy. In actuality, meanders can form on very steep slopes, for example, the slope of 1:12 in the meandering gully mentioned above. It does seem likely, however, that meandering in natural streams is promoted by low gradients and small discharges, for both Matthes and Friedkin have observed that lines of flow become straighter with increased discharge, while Friedkin and Quraishy find that increased slope tends to increase the meander wave length. The logical ultimate consequence of increased volume and velocity is described by Mathes, who concludes that if velocity could be coordinated with bed resistance by adjustment of bed width, a straight and wide but very shallow channel could theoretically result. Friedkin draws a similar inference. Chatley (1940) has developed the mathematical argument, starting with the Manning and similar flow formulae, and using the Kennedy-Lacey rule for bed stability. He considers that rectification of a meandering course would lead to a great reduction of velocity and hydraulic radius and a great increase of wetted perimeter.

Now these several conclusions are of the greatest importance in the present discussion. Their converse is that if a straight channel becomes more sinuous, the hydraulic radius and mean velocity increase, while the wetted perimeter is reduced. Thus a deeper channel with more stable banks can be maintained and a more efficient runoff occur than with a straight course. If this is so, it can easily be seen why a meandering course, once established, remains in being, and why also the dimensions of the curves are likely to be related to other dimensions of the channel.

MEANDERS IN RELATION TO STREAM SIZE

The initial cause of meandering has been investigated by a number of laboratory workers. It is probably a fair summary of the available results to state that meandering appears to originate primarily in the bed, with the simultaneous formation of shoals throughout the length of the channel. As White remarks (1939), "two distinct stages can be recognised, one in which the bed controls the banks, and another in which the banks control the bed, as in fully developed meander in nature." The initiation of meanders in nature can be witnessed only in such conditions as those of tidal flats: the wave length

of most valley windings was determined long since. Nevertheless it should be noted that meanders have been produced in laboratory streams, where the initial channel was straight, uniform in cross-section, and shaped in uniform and incoherent bed material, and where, moreover, the entrance was straight. Meandering is due to, or is at least related to, shoals which form for reasons not yet fully understood. Their development suggests a connection between the causation of meanders and the presence of a silt charge in the stream, especially since the shoals seem to be affected by the amount of load.[3] However this may be, it seems reasonably safe to state that in laboratory streams the amplitude and wave length of meanders have been found to be related most closely to discharge. Although Friedkin emphasizes the difficulty of description in mathematical terms on the grounds that the several variables form a circle of dependency, his own experiments produced uniform bends in constant conditions of slope and discharge. He accepted the general relationship between stream and meander size indicated by Quraishy and verified by Fisk.

Work based on field or map measurements of natural streams is likely, for obvious reasons, to take account of fewer variables than are considered in laboratory work. The values most easily determined are those of bed width W, depth D, wetted perimeter P, and values calculated from these; slope S; catchment area M; width of meander belt M_b and meander wave length (or interval) M_l. A group of important formulae make use of velocity V and discharge Q. For the purpose in hand it is necessary to consider whether a relationship exists in natural streams between Q, W (or P) and D on the one hand, and M_b and M_l on the other.

Quraishy's experimental work led to the equation:

$$M_l = \frac{32.6\ W}{(W/D)^{0.222}} \qquad (1)$$

in which it is clear that changes in bed width would have much greater proportional effects than changes in depth. Inglis (1941) has reanalyzed the data on natural streams presented by Jefferson (1902) and Bates (1939) and has found a statistical relationship connecting bed width, meander amplitude, and meander wave length. The equations relate only to rivers flowing in floodplains in open valleys—*alluvial rivers*. The original figures show a much greater amplitude of curves for incised rivers than for rivers not incised, part of which may be due to the ingrowth of curves; but since it is likely that river meanders have not always been separated in the measurements from valley meanders, the equations referring to incised rivers are not repeated here.

[3] Certain workers, whether explicitly or by implication, deny the necessity for a silt charge; some would compare stream meanders to the looped pattern of atmospheric jet streams and certain ocean currents. The matter cannot be pursued here, but reference may be made to the works listed below, by Baschin (1916), Exner (1919, 1924, 1928), Flohn (1952), Hjulström (1942, 1949), Kaufmann (1929), and van Rheden (1941).

From Jefferson's data Inglis finds that

$$M_b = 18.65\ W^{0.99} \qquad (2a)$$

or

$$17.38\ W \qquad (2b)$$

Bates' figures give

$$M_b = 10.9\ W^{1.04} \qquad (2c)$$

or

$$14\ W \qquad (2d)$$

These results may be compared with those of de Geer (1911) and with de Martonne's acceptance of $M_b = 18\ W$ for European rivers (de Martonne, 1935).

Inglis' analysis gives meander wave length as

$$M_1 = 6.06\ W^{0.99} \qquad (3a)$$

or

$$= 6.06\ W \qquad (3b)$$

from Jefferson's figures.

Some difference between formulae derived from different sets of data is not surprising, in view of the distortion to which individual meanders or meander trains are liable in nature, and considering also that bed width is not the only variable. It seems, however, that a fairly close relationship may be claimed, and the writer is prepared to accept a connection of the order given in equations (2a) to (2d).

SIZE OF MEANDERS, BED WIDTH, AND DISCHARGE

Inglis would go further and relate the width of meander belt directly to discharge (in cusecs) approximately as follows:

$$M_b = 57.8\ Q^{0.54} \qquad (4a)$$

or

$$84.7\ Q^{1/2} \qquad (4b)$$

An equation of this type depends on the assumption that bed width is related to discharge, and is, therefore, in accord with the work of Lacey, to whom a number of important channel formulae are due. Lacey concurs (1930) with the Lindley theorem that for a given discharge and silt factor the cross-sectional area, wetted perimeter, and slope of a stable channel flowing in and transporting its own silt are uniquely determined. Although in natural streams variations occur in silt factor, there is good reason to suppose that for a given value of S, discharge is by far the most important variable.[4] Lacey concludes that for stable channels in alluvium

$$P = 2.67\ Q^{1/2}, \qquad (5)$$

where P is the wetted perimeter in feet and Q the discharge in cusecs. This equation is claimed to be independent of silt grade (Lacey, 1938). Since in alluvial rivers W is approximately equal to P, it follows that $W \propto Q^{1/2}$. Inglis (1941) obtained a different constant, as follows:

$$W = 4.88\ Q^{1/2} \qquad (6)$$

but agrees, as has been noted, that P (or W), as also M_b and M_1, vary roughly as $Q^{1/2}$, and supports his contention by the analysis of various groups of data.

[4] The silt factor has been much debated, cf. White (1938), Schnackenberg (1951), and the discussions to Lacey's papers.

An equation of similar form, in which bed width is related to total annual discharge, is derived by Schoklitsch (1920) from a mass of data related to European rivers. Rewritten with the symbols used here, it becomes

$$W = \beta\,(CRM)^{0.6} \qquad (7)$$

where W is in feet, M the catchment area in square miles, R the annual rainfall in inches, C the coefficient of runoff, and β a bed coefficient ranging from 0.300 to 0.375. The advantage of this equation, for practical purposes, is that M may be obtained by planimetry, R from published data, and C from gauging records, or, if necessary, from rainfall records treated in the manner of Penman (1950) or Thornthwaite (1948).

CHANNEL FORM IN WINDING VALLEYS

Although there is clearly much room for additional work, the facts set out in the foregoing section are taken to verify a relation between discharge and bed width and between bed width and size of meanders. That is, a relation between discharge and size of meanders is taken as established. This conclusion appears to provide the required theoretical support for the view that valley bends are the work of former large streams—always supposing that the bends are identical in kind with stream meanders.

Mention has already been made of the evident similarity between the slopes developed at valley bends and the slopes eroded by an ingrowing meandering stream. It seemed to the writer that if the features were truly homologous the similarity ought also to appear in bed form. If large rivers had once occupied the winding valleys, it seemed possible that traces of their channels might still remain beneath the present alluvium, and that the bottom contours might be those typical of the bed of a meandering channel.

Six valleys have been investigated to date. Two lie in a formerly glaciated part of the English Midlands; one in the Cotswolds is a valley described by Davis, (1899); two in the Weald of southeastern England are outside the extreme limits of Pleistocene ice, and the sixth is in the Welsh Border country. In each valley the bed of the large river which cut the valley bends has been identified. The bottom contours are exactly appropriate to the channel of a meandering stream, very much larger than the existing river.

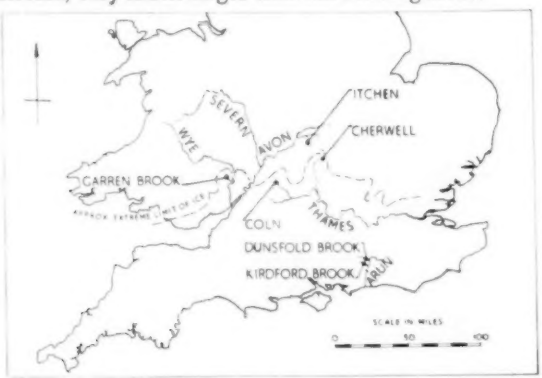


Fig. 3. Sites investigated in Britain, shown in relation to the farthest limit of ice.

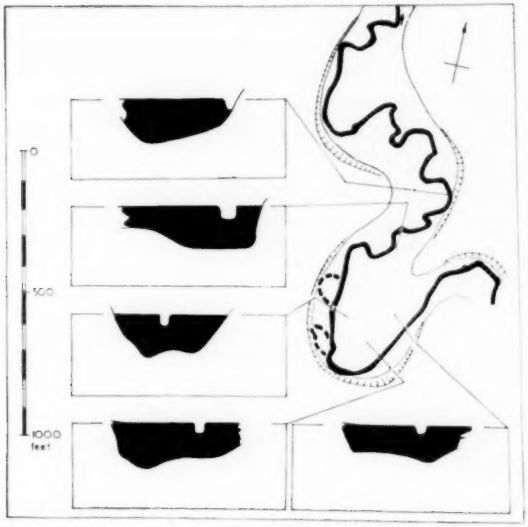


Fig. 4. Profiles of the filled channel on the Itchen, Warwickshire, England; catchment area approximately 9 square miles. Stipple on this and subsequent figures shows the present floodplain. Alluvium in solid black.

The Warwickshire Itchen has been best studied (figs. 3, 4, 5, 6). It is tributary to the Leam which in turn flows into the Stratford Avon. The valley was selected for investigation as containing impermeable alluvium underlain by impermeable solid rock, as not having been extended or reduced by divide migration since the last local glaciation, and as being tectonically stable. In part the valley is incised and winding, in part open and of very feeble relief but still with valley windings. On these counts none of the ad hoc explanations of valley bends, which were listed at the outset, could be postulated for the Itchen.

The windings are best displayed where the valley is incised into a limestone-shale series near the base of the Jurassic succession. The ribbon of alluvium which lines the valley bottom is for the most part sharply bounded in this reach by the base of the valley walls. The type features of winding valleys are well developed throughout—sinuosity on a large scale, steep slopes at the outside of valley bends, and gentle slopes on the inside, together with the small meanders of the existing stream. The latter, as is commonly observed, are mostly not in contact with the valley walls at many points but instead are described in the alluvium.

A number of auger holes were put down through the alluvium to the solid rock beneath, records of sample cores being kept, and the lines of working fixed by plane table on a base map of 1:2500 or 1:1250. The resulting data make it possible to draw sections through the valley bottom and, for some reaches, to construct contour maps of the base of the alluvium, as shown in the figures; these diagrams demonstrate the presence of a large meandering

channel. It is seen that in the Itchen valley the former channel, now filled by alluvium, underlies the whole flood plain. It is asymmetrical at valley bends, being deepest at the outside of curves and shallowing towards the inner side. Where the valley is inflected between one bend and the next, the floor of the old channel rises: here are evidently the former crossings, and the crescentic deeps at bends are the former swales.

It is not proposed to discuss in detail the nature of the alluvial fill, either in the Itchen or in other valleys, since the constitution of the alluvium varies greatly from one valley to another. In consequence it seems best to leave detailed local descriptions to local journals, where some accounts have already appeared (see References). It may be remarked, however, that in all the valleys it was possible broadly to distinguish two kinds of material. The floodplains are underlain by tenacious clay with impeded profile drainage; this in turn is underlain at many points by softer, moister material, which tends to become coarser in caliber at the base, and contains (or is much discolored by) plant debris. The former deposit appears to have settled out of floodwater, for all the valley bottoms are subject to flood, while the latter may well represent in part the former bed load but some of the characteristics noted belong to the development of a gley horizon in the soil. In most boreholes the junction between the alluvium and the solid rock beneath was very well defined. The solid, where consisting of limestone bands, was impenetrable; where argillaceous, it was dry, compact and tough, laminated in places, bright in color, abundantly micaceous but free of plant debris. In all these respects it contrasted with the alluvium. In other valleys solid rocks of different characteristics were found, but the junction in question was again clearly marked. The depths recorded in the diagrams are therefore looked on as wholly reliable.

It is important to observe that three different reaches of the Itchen were investigated, necessarily at different distances from the present source of the stream. It was found that the dimensions of the filled channel diminish headwards in about the same proportion as those of the existing channel. Hence the ratio between the respective widths of the two channels is the same throughout, as nearly as can be determined. Measurement is of course subject to a number of uncertainties, for the present banks are liable to be trodden down by cattle, while the filled channel seems to have shifted outwards at the bends; but the ratio of width can be roughly defined, by means of measurements at the respective crossings, as of the order of 10:1.

Now the same ratio appears in a comparison of the radii of curvature of the valley bends and the existing stream meanders in a group of streams in the English Midlands (Dury, 1951).[5] It also relates the widths of present and former channels near the head of the Cherwell (figs. 3, 7). What has affected the Itchen seems to have affected the Cherwell also, and to the same degree. Since the two streams are in competition, their loss of discharge cannot be due to capture.

[5] The writer is aware that the comparison of radii of curvature is not very satisfactory, and would recommend Leighly's paper of 1936 to fellow-investigators.

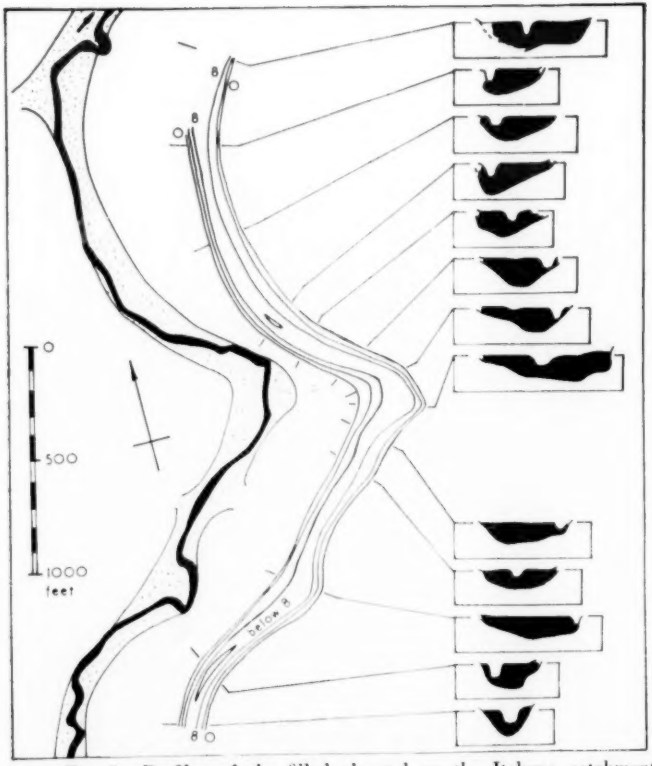


Fig. 5. Profiles of the filled channel on the Itchen: catchment area approximately 23 square miles. Contours show depth of channel floor below surface of floodplain, in feet. Map of present stream added for comparison.

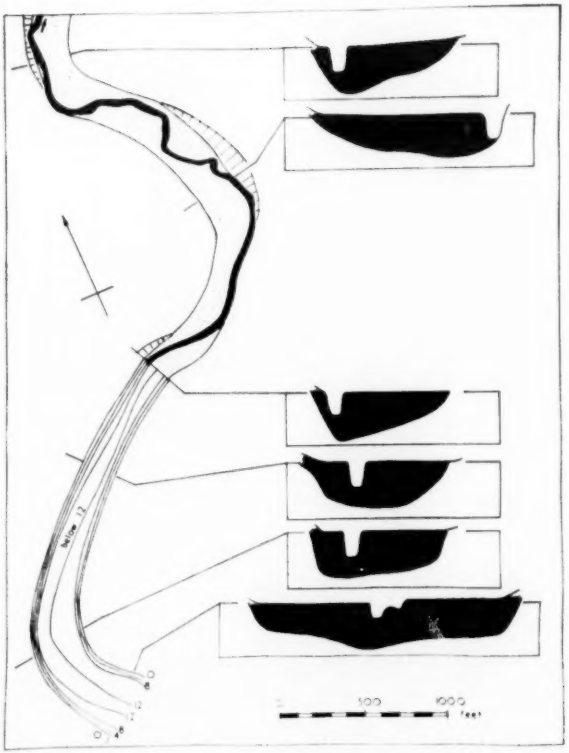


Fig. 6. Profiles of the filled channel on the Itchen: catchment area approximately 42 square miles. Contours in lower half as in figure 5; valley meander scars shown in upper half.

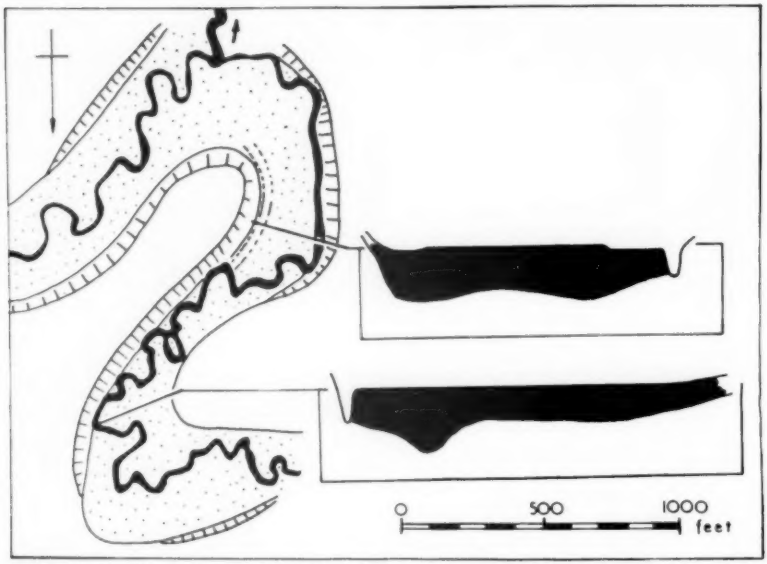


Fig. 7. Profiles of filled channel on the Cherwell, Northamptonshire, England. Form of valley walls indicated by symbols.

The Cotswold Coln (figs. 3, 8) is especially interesting in view of its use by Davis and Buckman to support the hypothesis of shrinkage through capture. Re-examination of the relevant reach of valley shows that both writers erred in identifying two sets of valley bends, which they took to indicate two successive captures. In fact there is only one set, in addition to the actively evolving loops of the present Coln. The field evidence is therefore wholly in accord with that of other localities, although there are complications. It is known that some water percolates into the subjacent oolitic limestone, so that the two channel widths can be less reliably compared. A knickpoint occurs in the middle of the reach investigated, and downstream from it the rejuvenated present stream has swept over much of the fill, planing off the solid floor beneath at some points. Nevertheless the general circumstances are similar to those known in the other valleys, and useful additional evidence is provided by local sludge gravels of Pleistocene age which demonstrably antedate the final cutting of the filled channel. The diagram shows that here too the present alluvium is contained in the channel of a former large meandering stream.

Percolation cannot have affected the two tributaries of the Sussex Arun (figs. 3, 9, 10) whose basins are largely underlain by Weald Clay, one of the great argillaceous formations of the Secondary succession. These streams moreover lie outside the limits of the Pleistocene ice sheets, and cannot have been affected by glacial meltwater or the discharge of proglacial lakes. The evidence secured in their valleys, however, closely resembles that from valleys in formerly glaciated parts. The filled channel is again present and is again

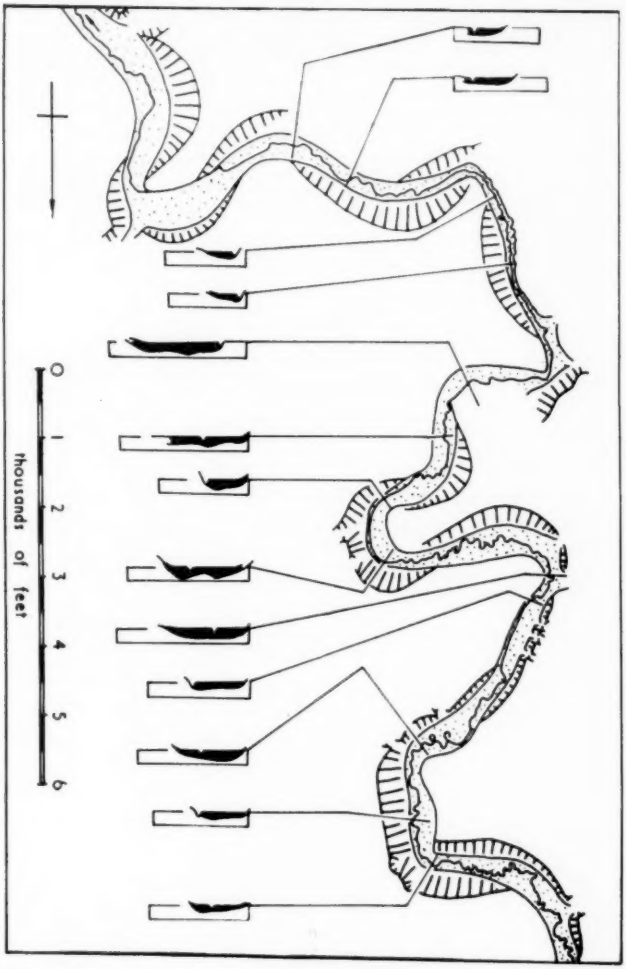


Fig. 8. Profiles of filled channel and form of valley walls on the Cotswold Coln.

asymmetrical at bends. It appears larger in proportion to the present stream bed than, for instance, the channel in the Itchen valley, but this is probably because the lines of augering run across valley bends where the old channel is laterally developed. The Garren Brook (figs. 3, 11), a tributary of the Wye, also drains a basin which is not thought to have been entered by ice. Here again a former channel encloses the alluvium. It will be seen that whereas the Itchen, Cherwell, and the two Sussex streams are not in contact with the solid rock except at the valley sides, and the Coln is eroding it only below the knickpoint, the Garren Brook has cut through the alluvial fill of the old channel and is becoming incised into the floor.

CHANNELS IN RELATION TO RUNOFF

In the writer's opinion, the qualitative results of field investigation are satisfactory and convincing as far as they go. It remains to be seen whether similar results will be obtained in other areas, particularly outside Britain, and it is hoped that the present account will stimulate others to join in the work. If the views advanced here are correct, comparable results are to be expected, although it need hardly be said that much variety of detail is likely to be found in practice. The matter need not, however, be left as it stands. Much additional light is thrown on the origin of the filled channels when their dimensions are compared with those of existing channels, and when they are considered quantitatively in relation to stream discharge and to size of drainage basins.

Data of bed width for both filled and present channels are given in table 1, together with areas of catchment. The length of wetted perimeter is stated only for the present channels, as it is difficult to determine bank level for the filled channels. The cross-sections show, however, that W and P were subequal in the latter.

In the small present channels matters are different. Depths are greater here in proportion to width, partly perhaps because the tenacious alluvium resists erosion and favors deepening at the expense of widening, but very largely because all the streams (except perhaps the Garren Brook) have been cleared in the course of drainage work. It may be noted in passing that the greater proportionate depths in the small channels have nothing to do with the principle of planimetric distortion (Lacey, 1934; Allen, 1947). According to this, depth in stream models [and in small streams] should be exaggerated in proportion to bed slope; but since the beds of the present streams are sensibly parallel to the known parts of the beds of the filled channels, there has been no significant increase in bed slope since the filled channels were in use. Indeed, when allowance is made for the greater tortuosity of the present streams, it appears that in some parts bed slope has actually been reduced.

Despite the uncertainties due to drainage works and to the difficulties of accurate and representative measurement, it is possible to obtain a rough relationship between the wetted perimeters or bed widths of the present streams, on the one hand, and stream discharge on the other. The linear measurements are made as at bankfull stage. Gauging records of flow are not plentiful in Britain, and in any event are not available for these small streams, but the mean annual discharge can easily be calculated from figures of rainfall minus losses.

It is interesting to observe the result of substituting *the mean annual discharge* for Q in Lacey's equation ((5) *supra*). Values for wetted perimeter P are obtained, which are about half the observed values, except for the Garren Brook; here the observed length of P is over four times that calculated. Although Lacey's equation is designed to apply to channels of constant discharge, and although its use in this way largely ignores the effect of fluctuations in Q, the similarity of results for all but one of the several basins is worthy of note. It suggests that the equation has a measure of validity in the

TABLE 1

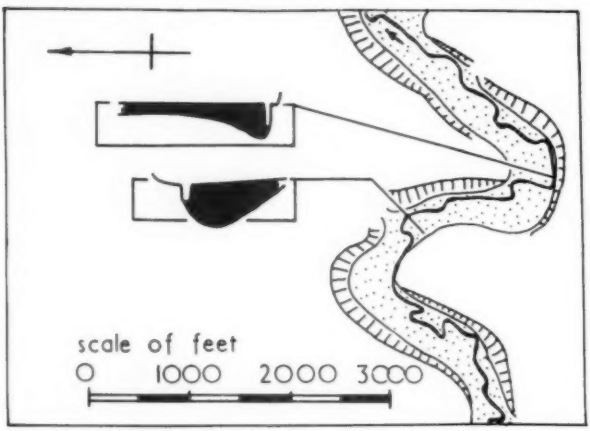
STATISTICS

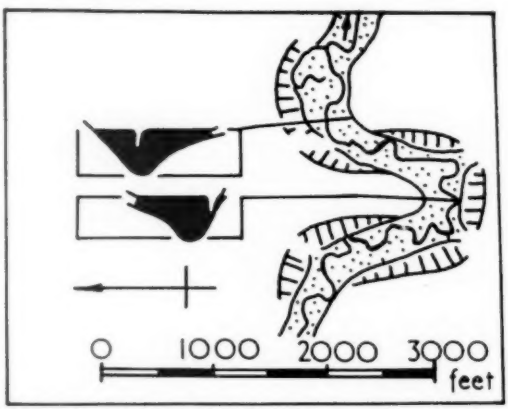
BASIN	Catchment area M, square miles	Present annual rainfall R in.	Present annual runoff, r in. of rainfall	Coefficient of annual runoff, r/R	Present bed width, W_p ft. approx.	Bed width calculated from Schoklitsch's equation, (7)	Correcting factor	Present wetted perimeter, P_p feet approx.	Wetted perimeter calculated from Lacey's equation, (5), using mean annual value of Q.	Correcting factor	Bed width of filled channel, W_r feet: approx. equals wetted perimeter P_r	Ratio of bed width between filled and present channels, W_r/W_p	Discharge of filled channel at bankfull stage if $Q = \left(\frac{P}{2.67}\right)^2$, in cusecs	Rainfall intensity, in./hr., required to fill large channels with water if i = Q/640M
Itchen (i)	8.7	25.0	9	0.36	8	5	1.6	13	6.5	2.0	100	12.5	1400	0.25
Itchen (ii)	23.2	25.0	9	0.36	15	9	1.7	20	10.5	1.9	150	10	3165	0.21
Itchen (iii)	42.3	25.0	9	0.36	20	13	1.5	32	14	2.3	200	10	5610	0.21
Cherwell	13.3	25.0	9	0.36	10	6.5	1.5	21	8	2.6	125	12.5	2180	0.26
Coln (i)	13.2	30.0	9	0.30	10	6.5	1.5	14	8	1.8	140	14	2750	0.33
Coln (ii)	16.9	30.0	9	0.30	12	7.5	1.6	16	9	1.8	130	11	2315	0.21
Dunsfold Brook (to Arun)	37.0	28.5	11	0.39	18	14	1.3	34	14.5	2.3	275	15	10600	0.45
Kirdford Brook (to Arun)	20.8	30.0	12.5	0.42	15	10.5	1.4	26	11.5	2.3	200	13	5600	0.42
Garren Brook (to Wye)	4.1	33.0	13	0.39	15	4.0	3.8	23	5.3	4.3	75	5	780	0.30

Note: Certain apparent slight discrepancies in the calculations are due to the rounding-off of some figures.

climatic regimes concerned, for a correcting factor of 2 is alone required roughly to relate bed width to mean discharge. The value of the correcting factor could usefully be compared with the values relating to other climates, always supposing that a simple relationship of this kind were found to exist.

Similarly, Schoklitsch's equation, ((7) *supra*), which is derived from measurements of actual rivers and relates channel size to area of catchment, gives values of bed width smaller than those actually found in the present stream, even when the constant β is taken at the maximum value of 0.375. The necessary correcting factor here is of the order of 1.5, again excepting the Garren Brook, for which the factor is 3.7. Schoklitsch's work relates to rivers under the influence of continental rather than maritime climates, and also to larger catchments; it is likely that these small English rivers are very sensitive to heavy falls of rain, for in their short courses there is no time for flood peaks to be smoothed out. The high observed values of P and W for





Figs. 9, 10. Profiles of filled channels and forms of valley walls on two tributaries of the Arun, Sussex, England.

the Garren Brook are especially noteworthy, as belonging to a stream with a much steeper gradient and hillier basin than any of the others.

As has been already stated, the bed widths of the filled channels are some ten times those of the present channels in the same localities (see also table 1). If it be supposed, for the sake of argument, that the relationship between the dimensions of the filled channels and the runoff of the time can be expressed by the Lacey or Schoklitsch equations, with the same correcting factors applied as in existing conditions, it appears that former discharges were equivalent to 300, 400, or more inches of rain per annum. There is no reason to suppose a priori that any such totals of precipitation occurred, but the figures are worth mentioning in order to emphasize that present totals, even without loss, could not provide the runoffs needed to cut the filled channels. It is evident that no concentration by snowmelt could explain the high runoffs which once took place, for according to Lacey's equation, the present total annual runoff could have been delivered by the filled channels, flowing at bankfull stage, in two days or less. The whole of the present annual precipitation, with no loss to percolation or to evaporation, could similarly have been run off in no more than five days. It is necessary therefore to postulate a former precipitation greater, and probably considerably greater, than that which is now recorded.

FORMER INTENSITY OF RAINFALL

The information available is not sufficient to indicate what in fact was the scale of annual precipitation when the large meandering channels were in use by streams. Enquiry may be more profitable directed to the probable former intensity of rainfall, i.e. rate of fall per unit of time. The rate is necessarily expressed here as the equivalent of runoff.

Admittedly the characteristics of individual drainage basins vary considerably. Too little is known of those investigated for use to be made of hydrograph analysis, even if the responses to very heavy falls could be accurately predicted. But simple flood-discharge formulae may be employed to show the *minimum* runoff equivalent needed to produce streams capable of filling the large channels to bankful. The best known is probably the Rational Formula:

$$Q_{max} = 640\ CiM \qquad (8)$$

where Q_{max} is the greatest expectable flood discharge past a given point, M the area in square miles of the catchment above that point, C a coefficient of runoff, and i the intensity of rainfall in inches per hour. Assuming a total (and extremely rapid) runoff, C becomes unity. The intensity of rainfall required to produce a given discharge is then given by

$$i = \frac{Q_{max}}{640\ M} \qquad (9)$$

Now the rates of discharge for the large channels can be found by means of Lacey's equation (5). When they are substituted for Q_{max} in equation (9), values of i are obtained as shown in table 1, column 15. The runoff equivalents correspond to rainfall intensities ranging from 0.20 to 0.33 inches per hour.

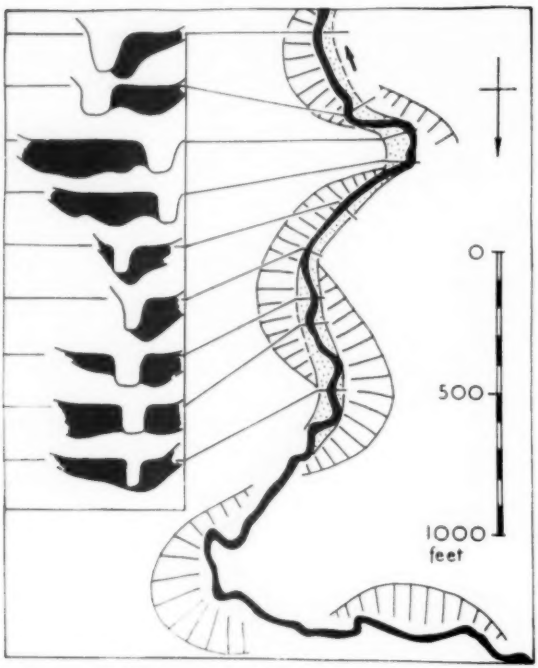


Fig. 11. Profiles of filled channel and form of valley walls on the Garren Brook, Herefordshire, England. Note incision of stream into the solid rock.

It may well appear significant that the values thus calculated are of the same order of magnitude in every case, although such a result might have been expected from the rough relationship of channel size to size of catchment.

It will be clear that the assumed connection between bed width, size of basin, and rainfall intensity expressed by the equations (5) and (9) can be used in a nomogram of the form shown in figure 12. Given values of M, and of W for the filled channels, the values of i can be read off directly.

At the present day, rainfalls of 0.20 in./hr. are to be expected in the basins studied on about 10 days a year, while the expectable frequency for falls of 0.35 in./hr. is only about 2 days. The scanty records available seem to indicate that the existing streams rise to, or above, bankfull stage on perhaps 10-20 days in an average year. This fact appears to confirm the implication in the foregoing, that the present channels are inadequate to cope with discharges produced by a rainfall intensity which was formerly usual rather than exceptional. The particular line of reasoning followed here further suggests that the large channels could have been cut when the total annual fall was considerably less than the 300 inches referred to above, but an actual figure cannot be derived without assuming some relationship between the rainfall intensity and the annual total. It should be noted, however, that if the large channels are to be associated with the compression of storm tracks

TABLE 2

Correlations: Based on the Work of Arkell, Flint, Shotton and Zeuner

	North America	Alps	Continental Europe	English Midlands	Midland Rivers—Nene, Ouse and Avon	Oxford Rivers —Cherwell and Windrush	Oxford Rivers—Evenlode
Postglacial					Valley bends of Avon eroded as far as postglacial time		Valley bends of Evenlode evolve into postglacial time
Glacial	Wisconsin	Würm	Warthe, etc.	Welsh re-advance (Cymrian of Arkell) Irish Sea Glaciation (Cornovian of Arkell)			
Interglacial	Sangamon	R/W				Floodplain gravel in valley-bends Taplow gravel in valley bends	
Glacial	Illinoian	Riss	Saale	Great Chalky Boulder Clay (Catuvellaunian of Arkell)	Warwickshire Avon Initiated		Evenlode gorge initiated
Interglacial	Yarmouth	M/R			Great Ouse valley meanders incised	Boyn Hill gravels in valley bends	
Glacial	Kansan	Mindel	Elster	Older Drift, Northern Drift (Berrocian of Arkell)			
Interglacial	Aftonian	G/M			? Nene valley already cut?		
Glacial	Nebraskan	Günz					

in parts of the Pleistocene, the highest rainfall intensities may not have departed greatly from the modal intensity, and that 300 inches could have fallen in less than 900 hours at a rate of 0.35 in./hr.

DATING THE EPISODES OF GREAT DISCHARGE

A discussion on climatic change cannot be initiated here, but two facts may be remarked in passing. Recent studies (Hoyt et al., 1936) indicate that rivers are extremely sensitive to changes in precipitation, while a number of well-known authorities postulate increased rainfall in mid-latitudes during the Pleistocene, often associated with the displacement of storm tracks (Willett, 1949, 1950).

For the time being it seems more important to consider the dating of winding valleys. There is good reason to place the inception of some, at least, well back in the Pleistocene, while the filled channels so far studied all seem to have been in use in Holocene time. A few significant examples must serve to illustrate the progress, admittedly limited, made to date in drawing up a

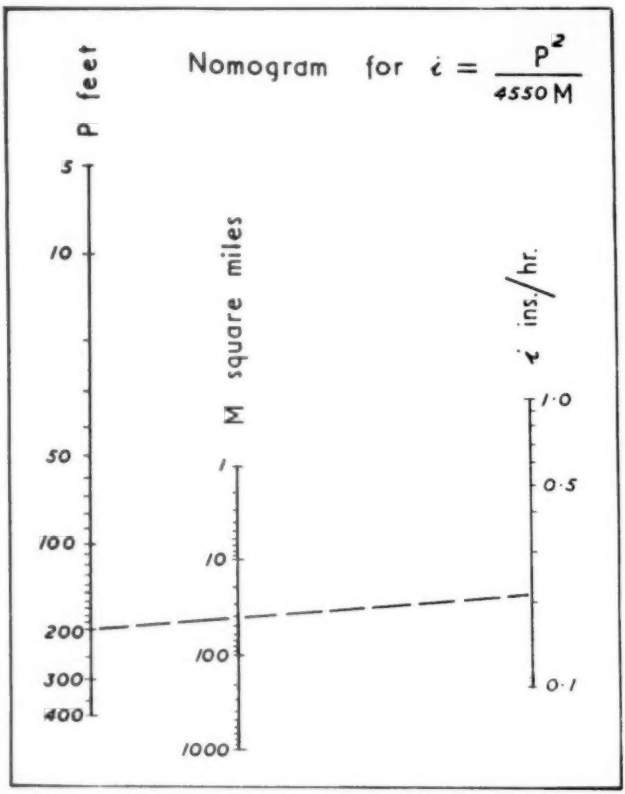


Fig. 12 Nomogram relating bed width of filled channels to minimum rainfall intensity required to produce adequate streams.

time scale. The results are summarized in table 2, where they are tentatively referred to the North American chronology recognized by Flint (1947).

The great abandoned loops of the Wye lie well above the river, in one instance about 400 feet (Davies, 1923; Miller, 1935). In the Oxford District, valley loops include, and therefore cannot postdate deposits of gravel *in situ* ranging in age from Boyn Hill to Flood Plain (Yarmouth to Sangamon) (Davies, 1923; Arkell, 1947). The great loops of the Stratford Avon seem to have swept out a meander trough at the no. 2 Terrace stage (Dury, 1951; Tomlinson, 1925). On the Seine, the train of valley bends from Rouen to Chizier seems to have appeared at the end of the Tyrrhenian [sic] glaciation (Cholley and Firmin, 1945). Valley bends of the Great Ouse are plugged by till of an ice sheet correlative probably with the Riss of the Alps (Dury, 1952). In the Fenlands of eastern England, old channels are known which describe loops more ample than those of the existing stream. Pollen analysis shows (Godwin, 1938, 1940) that the channels were cut at least as early as the pre-boreal period, by large streams which underwent a reduction of volume at least as early as 7500 B. C.

The evidence could be multiplied by reference to well-studied terraces, but perhaps enough has been said to indicate the interconnection of winding valleys and Pleistocene climates. A leading principle for future work on the chronology must obviously be that a winding valley is later than an erosion platform into which it is cut, and at least as early as the deposits which it contains. The most difficult task, however, appears to be the dating of the latest use of the filled channels; here radiocarbon dating and pollen analysis might help in fixing the age of the fill, but it is highly desirable to locate examples of valley bends incised into rocks as young as possible.

IMPLICATIONS

If valley bends are indeed the meanders of great streams, and if these were fed by rainfalls of the intensity inferred here, a number of further problems at once arise. The question of stream grade and of valley gradient in the areas affected needs to be re-examined. It follows from slope-discharge formulae and from the theory of stream models that a general reduction of discharge should lead to an increase in slope. But since aggradation seems to have made little headway in the valleys studied, the valley gradients seem to be related to former rather than to present discharges. Therefore the present streams cannot be graded in the Davisian sense. It necessarily follows from this conclusion that attempts to relate long profiles to present discharges are based on a false assumption.

The problem of dry valleys, especially in Chalk country, must also be considered anew. It is widely held (although not universally) that the valleys have been left dry as the water table was lowered by excavation of the water-retaining beds below the Chalk. But since the occurrence of valley windings has been shown to be independent of movements of the water table, it must be asked what would be the effect on dry valleys of frequent and heavy falls of rain. Even today, when underground circulation is presumably better organized than ever before, temporary streams appear in some dry valleys in

unusually wet seasons. It is at least permissible to suggest that, when large rivers were eroding the valley bends, many valleys of Chalk tracts were occupied by streams, and that a return to former climatic conditions would again produce surface flow in areas now dry. On this view, lowering of the water table is due primarily to climatic change rather than to erosion.

A third important topic is that of process. Climatic change necessarily involves change in the relative effectiveness of erosional processes, and many recent studies suggest that small changes in climate may well bring additional processes into play. Increased rainfall intensity should favor the operation of sheet flood and sheet erosion in areas where rainwash, rillwash and creep are now dominant. This subject again is far too complex to be dealt with here, even in summary, but the suggestion made may seem to point the way to a solution of certain refractory problems of landscape evolution in humid as well as in arid climates.

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PRESSURE-VOLUME-TEMPERATURE RELATIONS IN CO_2 AT ELEVATED TEMPERATURES AND PRESSURES*

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ABSTRACT. Carbon dioxide is probably the second most geologically important gas. Interpretation of hydrothermal systems and work on the stability of carbonate minerals has been greatly hampered by a lack of information concerning properties of carbon dioxide. Measurements are presented in this paper of the pressure-volume-temperature relations of carbon dioxide gas to maximum temperatures of 1000°C. and pressures of 1400 bars. The technique and the equipment involved in making the measurements is discussed.

INTRODUCTION

Among the gases of greatest interest to geologists, CO_2 ranks second in importance to water. Most volcanic gases contain at least 20 percent by weight of carbon dioxide. By analogy we may assume that similar amounts of CO_2 are contained in ore-forming solutions. This CO_2 will probably lower the critical temperature of the resultant solution and hence may play a role in determining whether such a solution is gaseous or liquid.

Experimental work by John R. Miller (1952) in the writer's laboratory on the system $CaCO_3$—H_2O—CO_2 was terminated at very modest temperature and pressure limits because of a lack of the fundamental P-V-T relations of CO_2 and for lack of data on the system CO_2—H_2O. Experimental study of many of the most interesting reactions involved in contact metamorphism similarly must await the determination of the properties of CO_2 and CO_2-H_2O mixtures. For these and other reasons, the P-V-T relations of CO_2 have been determined to 1000° C. and 1400 bars, and are recorded in this paper.

A good deal of previous work has been done on CO_2. Most of this has been included in the volume *Carbon Dioxide* (Quinn and Jones, 1935). The important early work is that of Amagat (1880), who measured densities and pressures of the gas up to approximately 200° C. and 1000 bars pressure. This work was published in 1880, and Amagat's measurements above 150° C. at high pressures remain the only work in this portion of the field to the present time. McCormack and Schneider (1950) have recently published the results of some accurate measurements to 50 bars pressure and to 600° C.

The results of some exceedingly precise measurements at temperatures up to 150° C. and pressures to 3000 atmospheres were published by workers at the Van der Waals Laboratory in Amsterdam (Michels and Michels, 1935). Unfortunately, the beautifully precise methods used by the Van der Waals Laboratory are not practical at high temperatures, since mercury, which is used to seal the gas, boils at 375° C. at 1 atmosphere pressure. Moreover, the pressure vessels were not designed to withstand high pressures at high temperatures. The values of density reported in this paper are reproducible to 1 part in 500 where those of the Van der Waals Laboratory have a precision of 1/10,000.

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APPARATUS AND TECHNIQUE

The general apparatus and method of measurement utilized in the present investigation have been described in part in an earlier paper (Kennedy, 1950). Some modifications of the method, however, have been made.

The volumometer.—Two volumometers were used in the present work. Their design is based on the volumometers described by Keyes (1933). One of the volumometers has a ½ inch diameter piston and the other a ¼ inch diameter piston. The lead screws of the volumometers were precision lead screws made by the Waltham Machine Works with a maximum tolerance of ±0.0003 in. in total length. Several samples of water from the volumometer were collected and weighed by advancing the lead screw over various portions of its length. They indicated that the lead screw and piston were uniform to within 0.00001 grams/turn.

The larger volumometer was used for measuring the volume of material injected into a bomb and was calibrated by weighing quantities of water

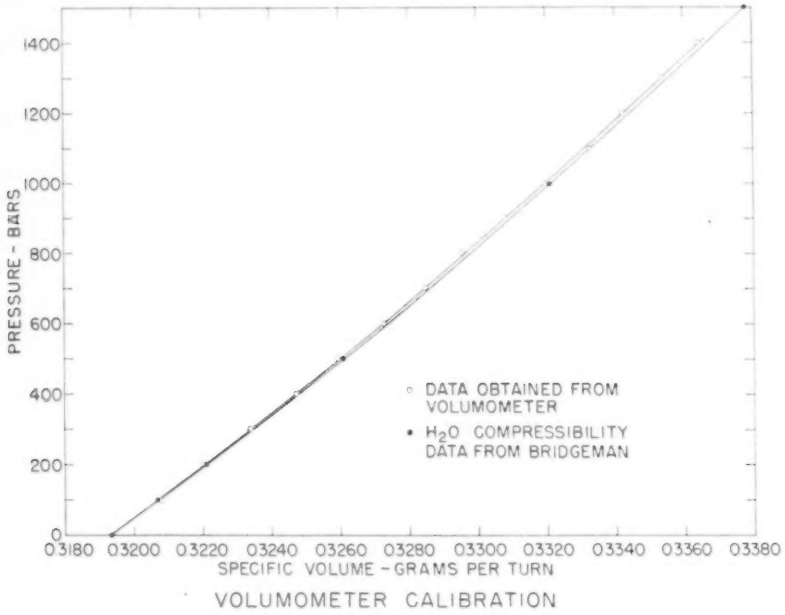

Fig. 1.

extruded at various pressures. The calibration, showing grams water expelled per turn, is shown in figure 1. This is compared with a curve, computed from Bridgman's data (1935) on water compressibility, without correcting for the pressure distortion of the volumometer. The difference between the two curves, which amounts to approximately 0.044 percent per 1000 bars pressure rise, is largely due to compression of the volumometer piston. Taking Young's modulus for steel to be 30.0×10^6 p.s.i., a correction for compression of the piston amounts to 0.049 percent per 1000 bars; thus the agreement with

Bridgman's data is excellent. Further details concerning the calibration of the volumometer will be presented in a paper now in preparation on density measurements of water.

Bomb.—The bombs used in these measurements were similar in design to those previously described (Kennedy, 1950) with but a minor modification. A tube of stainless steel of 0.25 in. o.d. and 0.06 in. i.d., closed at one end, was threaded through the bottom of the bomb and welded in place. The thermocouple wires, coated with quartz glass, were inserted in the tube so that the thermocouple junction rested near the center of the bomb. By this method uncertainties concerning the temperature of the bomb contents were largely reduced.

Bombs used in these measurements were of the order of 200 to 300 cc capacity.

TEMPERATURE CONTROLS AND MEASUREMENT

The bomb was heated in an electrical furnace 30 inches in length with an inside diameter of 3 inches. The ends of the furnace were stuffed with a mixture of magnesium oxide and asbestos. Exploration of the closed bomb cavity with a thermocouple indicated a temperature inhomogeneity of less than $\pm 0.1°$ C. at 400° C.

The furnace temperature was regulated by means of an alternating current bridge and phase-shifting thyratron circuit. Xenon-filled, tantalum anode thyratron tubes were used, with a maximum output of approximately 6 amperes at 200 volts. Temperature regulation over most of the range was to within $\pm 0.5°$ C., though at no time in the course of the measurements was it necessary to hold the temperature at a given value for a long time.

Temperatures were measured by determining the e.m.f. of a platinum-platinum 10% rhodium thermocouple on a shielded, type K potentiometer. Four thermocouples were made up from the same spools of 0.020″ wire obtained from Baker & Co., Newark, New Jersey. They were annealed for 50 minutes at 1400°C. and then compared with each other by placing the junctions of the couples in four closely spaced holes drilled in a stainless steel block. The block was then heated in the center of the 30 in. furnace, used to heat the bomb. The couples agreed with each other to $\pm 0.05°$ C. in the region from room temperature to 1000° C. One of these couples was then calibrated against the boiling points of water and sulfur, and the freezing points of antimony, copper, and gold. A second thermocouple was calibrated at the National Bureau of Standards. The Bureau of Standards certified the e.m.f. of this thermocouple at the thermometric fixed points, the freezing points of zinc, antimony, silver, and gold. The accuracy of this certification was 2 microvolts, about $\pm 0.2°$ C. In addition they certified 15 corresponding values of e.m.f. and temperature to an accuracy of $\pm 0.3°$ C. in the range 0 to 1100° C. and from $\pm 0.3°$ C. at 1100° C. to $\pm 2°$ C. at 1450° C. The two thermocouple calibrations agreed with each other within the limits of accuracy of certification. The two calibrated thermocouples were then placed to one side and only used when the four thermocouples were compared against each other. One of the thermocouples, after over a year of use at temperatures below 1000° C., showed a drift in calibration of less than 0.1° C.

Pressure measurement.—Three Bourdon tube gauges, manufactured by the Heise Bourdon Tube Co., were used in the present work. The gauges covered the ranges 0-100 bars, 0-500 bars and 0-1400 bars. Gauge dials were graduated in 1000, 1000 and 1400 scale divisions respectively. The gauges were calibrated by the manufacturer against a dead weight gauge and gave a maximum uncertainty in the readings over most of the range of approximately one scale division owing to hysteresis. At the highest pressures, 1400 bars, hysteresis became slightly greater. After a good deal of work had been done, it became apparent that some drift of a few tenths of one percent in the calibration of the gauges had taken place. Consequently the dead weight piston gauge, previously described by Benedict (1939), was set up and the gauges were thereafter checked on the dead weight tester at regular intervals. The earlier work was then systematically re-examined and appropriate corrections made.

CARBON DIOXIDE GAS SUPPLY

The carbon dioxide gas used in the experiment was made by New England Alcohol Co., a subsidiary of Monsanto Chemical Co., and supplied through the New England Gas Products Co. The CO_2 gas is supplied as "bone dry" and has a purity of 99.6 percent top sample. As the gas in a cylinder is used the purity increased to better than 99.9 percent when 50 percent of the tank has been expended. It was thus standard practice to bleed off the top portion of the tank and use the bottom half for the gas measurements. No correction was made for impurities in the gas; nitrogen is the major impurity.

Although the gas was supplied as "water free," small droplets of water and oil were soon detected in the supply line extending from the carbon dioxide cylinder to the bomb. A trap was therefore installed in the system and the gas passed through several inches of loosely packed anhydrous magnesium perchlorate before it was loaded into the apparatus. This effectively removed traces of oil and moisture from the gas.

EXPERIMENTAL METHOD

Two different methods were used to obtain the present data. A set of measurements at 25, 50, and 75 bars pressure and measurements at gas densities of less than 0.10 g/cc along the 150° C. isotherm were obtained by injecting known quantities of gas, via the capillary tubing, into the bomb. The volumometer was maintained in an ice bath and was always read at 0°C. and 100 bars pressure before and after gas was injected into the bomb. The schematic diagram of the apparatus is shown in figure 2. For example, a point on the 50 bar curve is obtained in the following fashion: The system is first flushed several times with carbon dioxide. Needle valves no. 3 and no. 4 are then opened and the volumometer allowed to fill with gas at tank pressure. Tank pressure, the pressure of gas over liquid CO_2, ranged from 55 to 70 bars depending on room temperature. The gas condenses in the cold volumometer, which fills rapidly, though about ½ hour usually is required before the volumometer returns to 0°C. as considerable latent heat of con-

densation is liberated. Next V-4 is closed, V-2 is opened, and the piston in the volumometer is advanced until Gauge no. 1 reads the desired pressure, 50 bars. V-2 is then closed and the piston advanced until Gauge no. 2 reads 100 bars. At this point, the piston position is read. V-1 and V-2 are then

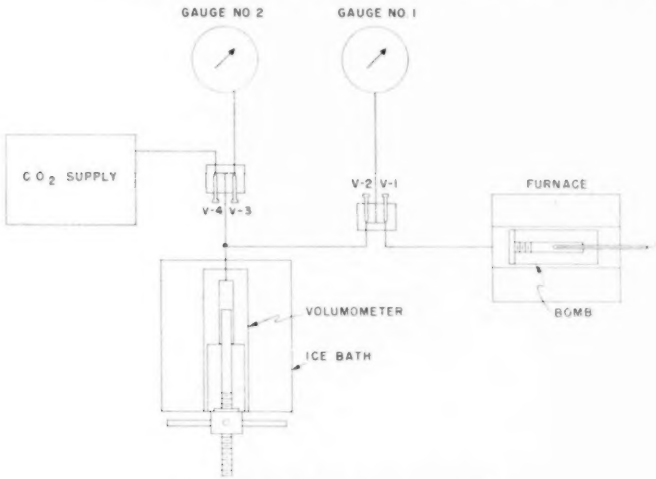

FIG 2 SCHEMATIC DIAGRAM OF APPARATUS

opened, allowing gas to flow into the bomb. The volumometer piston is again advanced until Gauge no. 1 reads the desired 50 bars. About 15 minutes is required at this point for attainment of equilibrium between the gas and the bomb. V-2 is then closed and the piston advanced until Gauge no. 2 reads 100 bars. The final position of the piston is then read. The difference in cc between the two piston settings, multiplied by the density of CO_2 gas at 0°C. and 100 bars, 0.9690 g/cc, gives the amount of gas forced into the bomb. No corrections are made for the amount of gas required to deflect the gauge, fill the valve block, or fill the capillary tubing between gauge and volumometer, for the pressures on this part of the system are the same before and after the piston settings are read. The only correction that might be made is that for the volume of the capillary tubing between V-1 and the bomb. The tubing is of 0.100 in. outside diameter, 0.019 in. inside diameter, and 14 in. in length. This volume amounts to approximately 0.06 cc and is negligible in terms of the volume of the bombs (200 to 300 cc). Consequently these corrections were not made.

The density of gas at 0°C. and 100 bars in the volumometer was determined by measuring with the volumometer the quantity of gas required to bring a bomb at 0°C., of known volume, to a set of pressures and corresponding densities reported by Michels for 0°C. Michels gives values of densities for 0°C. for the pressure range 16.55 bars to 33.42 bars. The results of Michel's and others are reported in Amagat units, i.e. the ratio of the density of carbon dioxide to its density at 0°C. and 1 atmosphere pressure. In this paper, where densities are reported in g/cc, an Amagat unit is as-

sumed to be 0.0019767 g/cc (Quinn and Jones, 1936, p. 35). Using this conversion factor, Amagat's density for carbon dioxide at 0°C. and 100 bars pressure is approximately 0.9775 g/cc. This differs sharply from the writer's present value of 0.9690. These grossly differing values are not as alarming as first appears. Amagat's value probably is somewhat in error; on the other hand, it seems likely that the writer's volumometer, though in an ice bath, was not exactly at 0°C. The piston of the volumometer projects from the ice bath to a driving screw, and some heat conducted down the piston may well hold the contents of the volumometer slightly above 0°C. The density of carbon dioxide changes very rapidly with temperature in this region, and if the volumometer were as much as 1°C. above 0°C. most of the difference between the two values would be accounted for. The exact conditions of the volumometer need not be precisely known, however. For the purpose of the present work, it need only be known that steady state conditions hold and that the CO_2 liquid at 100 bars pressure as it emerges from the volumometer has a density of 0.9690 g/cc. This was amply proved by repeated checks of the data of Michels and his co-workers.

The previously described method of measuring gas densities is a slow and tedious one, largely because of the sharp temperature changes which take place in both the pressure gauge and the volumometer as the CO_2 liquid vaporizes and condenses under the abrupt pressure changes involved. Consequently much time is spent waiting for temperature to equalize over the various parts of the apparatus external to the furnace.

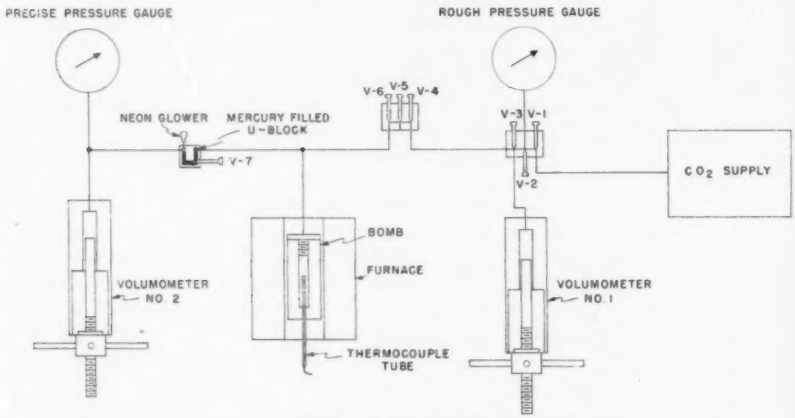

FIG. 3 SCHEMATIC DIAGRAM OF APPARATUS

Because of these difficulties, a second method was devised, the apparatus of which is shown in figure 3. This apparatus is designed to measure P and T on a constant quantity of gas under approximately constant volume conditions. As temperature and pressure changes affect the volume of a bomb, it is impossible to make measurements under precisely constant volume conditions.

The essential difference in this apparatus from that of figure 2 is in the use of an insulated needle connected with a neon glower to locate the surface of mercury in a U block. V-7 in the U block is closed and the piston in volumometer no. 1 is advanced until a quantity of gas, which is not measured, is introduced in the bomb. The piston in volumometer no. 2 is then advanced until the two pressure gauges are at approximately the same value. V-6 is next closed, V-7 opened, and volumometer no. 2 is adjusted so that the level of mercury is exactly at the tip of the insulated needle as indicated by the neon glower. The bomb is slowly heated and a plot of pressure versus temperature made. The piston in volumometer no. 2 is advanced for each reading to restore the level of mercury in the U block to its proper position at the tip of the insulated needle. By this method the contents of the bomb remain the same throughout the heating cycle, and the fluid required to deflect the pressure gauge, in this case kerosene, is supplied from the volumometer. No correction was made for compressibility of mercury in the U block, as this is negligible. Great care was exercised in the construction of the apparatus, particularly in construction of the T joint, where the capillary tubing from the bomb, the U block, and the loading apparatus meet, so that this part of the apparatus would be of minimum volume. Total volume of the tubing and connections between the bomb and the surface of the mercury is approximately 0.10 cc which contrasts favorably with the volume of the bomb, approximately 200 cc.

For each filling of this apparatus, the pressure measured at 150° C. can be used to find the density in Amagat units (A.U.) of the CO_2 at this pressure and 150° C. This information can be obtained from Michels' density-pressure data for the 150° C. isotherm. The density of the gas in the bomb can be then determined in g/cc by

$$d(g/cc) = d(A.U.)\ d_N(g/cc)$$

where

d_N is the gas density at N. T. P.

For CO_2, $d_N = 0.0019767$ g/cc.

For a fixed quantity of gas, the density will vary with T and P inversely as the bomb volume varies. Hence d for any pair of values of T_2 and P_2 can be determined from $d(150°, P_2)$ provided the thermal expansion and pressure dilation of the bomb are known.

The major advantage of the latter method of determining P-V-T relations is that it is unnecessary to know the volume of the bomb used in the measurements or to meter the amount of gas injected into the bomb. It is necessary, however, to have an accurate reference isotherm such as the 150° C. isotherm supplied by Michels. Michels' data, however, extend only to gas densities as low as 0.03706 g/cm and reference data at much lower densities are needed. These low density reference data were obtained by the first described method, that of injecting known quantities of gas into a bomb of known volume.

In both methods it is necessary to make corrections for thermal expansion and pressure dilation of the bomb. The thermal expansion correction is

very straightforward and, for instance, with bombs of type 347 stainless steel, amounts to

$$\begin{aligned} 20° - 100°C., &\quad 0.3576\% \\ 20° - 500°C., &\quad 2.520\% \\ 20° - 1000°C., &\quad 5.703\% \end{aligned}$$

Only an approximation can be made for the correction due to pressure dilation of the bomb.

Change in radius of the bomb under pressure was computed from the following formula:

$$\Delta r = \frac{a^2P}{(b^2-a^2)E}\left\{(1+\mu)\frac{b^2}{r} + (1-\mu)r\right\}$$

and at $r = a$

$$\Delta a = \frac{a^2P}{(b^2-a^2)E}\left\{(1+\mu)\frac{b^2}{a} + (1-\mu)a\right\}$$

where Δr is the change in internal radius, μ is Poisson's ratio 0.30, $E = 30X10^6$ p.s.i., P is internal pressure, a is internal radius and b is external radius. This formula is applicable to an infinitely long tube under pressure. In this particular case the ends of the bomb and the longitudinal stresses present will partially restrain deformation and the actual volume change will be somewhat less than computed. The total volume change of the bomb due to pressure has a maximum value of 0.084 percent per 1000 atmospheres, and as this is within the limits of error in reading the pressure gauges, further refinements were deemed unnecessary. It was assumed that Poisson's ratio and Young's modulus of the bomb metal remained approximately constant over the operating temperature. This is a fair approximation over much of the temperature range, but at the highest temperatures this must remain only an assumption.

RESULTS

Curves determined by simultaneous measurements of P and T were plotted for a large number of different d values in the bomb. In total, several thousand measurements were made. These were smoothed and corrected for bomb expansion to make the best isochore for each bomb filling. Isobars and isotherms were then constructed and smoothed graphically to make the best fit to the values taken from the isochores. Density values in g/cc were read directly from the isobaric plots. Tables of differences between adjacent values were then made up along the isobars and the last figure in the density value was adjusted to give smooth differences. These final values are the ones reported in the accompanying table 2 (p. 236ff.).

All the values in the accompanying table were determined, as indicated above, from the isochore data obtained by the second method described in this paper. However, the first and second methods described gave essentially identical results. The smoothed values obtained by the "constant volume"

method, expressed to four places, are shown in the following table 1. These are compared with the direct values obtained by the volumometer.

TABLE 1
Comparison of Results from Constant Volume Method with Results by Volumometer

	25 bars		50 bars		75 bars	
T° C.	Volumometer	Constant volume	Volumometer	Constant volume	Volumometer	Constant volume
200	.02881	.0288				
300	.02326	.0233	.04682	.0468		
400	.01960	.0197	.03927	.0393	.05909	.0591
500	.01705	.0171	.03390	.0340	.05089	.0509
600	.01511	.0151	.03008	.0301	.04500	.0449
700	.01348	.0135	.02693	.0269	.04031	.0402
800	.01221	.0122	.02442	.0244	.03666	.0364
900	.01122	.0112	.02234	.0223		

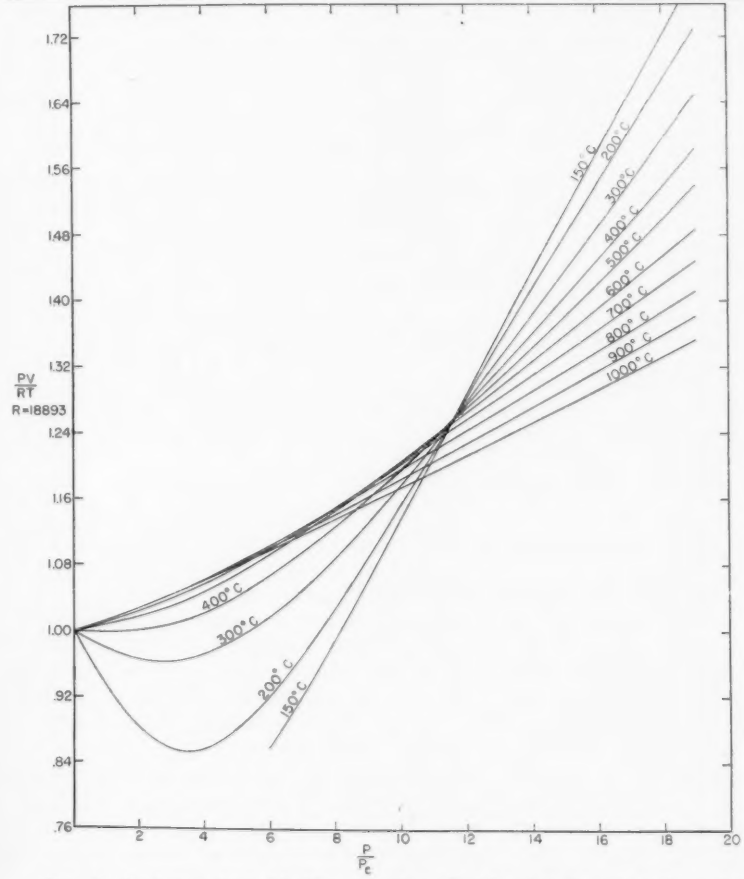

Fig. 4. Deviation from ideality of carbon dioxide plotted against the reduced pressure.

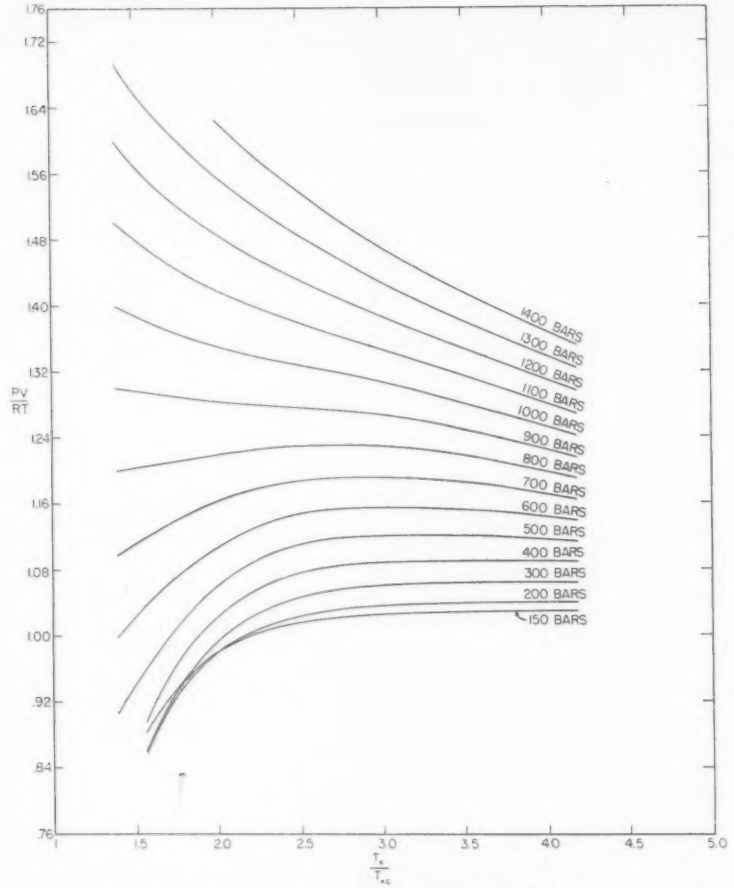

Fig. 5. Deviation from ideality of carbon dioxide plotted against reduced temperature.

The agreement between the two sets of results is satisfactory.

Little can be said about the accuracy of these measurements. Throughout the region where the present body of data overlaps that of Michels and of McCormack and Schneider, the two sets of data agree to 0.0001 g/cc or 0.2 percent, whichever is the larger. At high temperatures, the lack of any body of data for comparison and the possibility of reaction between bomb wall and gas makes all claims to accuracy somewhat meaningless. The writer is, furthermore, in the embarrassing position of having claimed accuracies at high temperatures in an earlier paper on P-V-T relations of water which later proved to be unjustifiable, largely because of reaction between the water gas and the bomb alloy. The reproducibility of the present set of data is high, and

the smoothed values reported in the tables differ from the experimentally determined values by 0.4 percent or .0002 g/cc, whichever is the greater, for the largest changes introduced by the smoothing procedure.

The present results are summarized and presented in figure 4 and figure 5. In these figures the deviation from the ideal gas law is shown. In figure 4, the value PV/RT is plotted against the reduced pressure, P/Pc, where P is the P observed and Pc is the critical pressure of 73.82 bars. In figure 5, the value PV/RT is plotted against T/T_c where T is the temperature, on the Kelvin scale and Tc is the critical temperature, 304.2° K.

ACKNOWLEDGMENTS

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TABLE 2

Density CO_2 in g/cc

Pressure in Bars

T°C.	25	50	75	100	150	200	250	300	350	400	450
0	.0601	.947	.954	.969	.997	1.0170	1.0350	1.0530	1.0670	1.0792	1.0900
10	.0561	.864	.891	.914	.950	.9770	1.0000	1.0190	1.0350	1.0502	1.0635
20	.0527	.1423	.810	.855	.901	.9335	.9600	.9832	1.0030	1.0200	1.0351
30	.0499	.1251	.655	.782	.850	.8887	.9190	.9460	.9685	.9882	1.0054
40	.0476	.1135	.2305	.638	.785	.8415	.8771	.9077	.9339	.9559	.9755
50	.0456	.1052	.1932	.3901	.705	.7855	.8347	.8687	.8990	.9233	.9451
60	.0437	.0984	.1726	.2868	.604	.7240	.7889	.8292	.8634	.8905	.9139
70	.0421	.0930	.1584	.2478	.504	.6605	.7379	.7882	.8270	.8575	.8821
80	.0405	.0883	.1469	.2215	.430	.5935	.6872	.7466	.7898	.8243	.8516
90	.0391	.0845	.1381	.2019	.373	.5325	.6359	.7040	.7522	.7909	.8212
100	.0378	.0810	.1305	.1877	.333	.4815	.5880	.6630	.7160	.7571	.7911
110	.0366	.0778	.1239	.1765	.304	.4378	.5443	.6230	.6805	.7250	.7613
120	.0354	.0749	.1187	.1673	.280	.4015	.5053	.5855	.6460	.6938	.7321
130	.0344	.0722	.1141	.1595	.262	.3718	.4718	.5517	.6129	.6642	.7048
140	.0334	.0697	.1094	.1525	.2465	.3470	.4419	.5200	.5824	.6352	.6771
150	.0325	.0674	.1054	.1461	.2337	.3267	.4151	.4925	.5549	.6079	.6501
160	.0316	.0653	.1018	.1403	.2229	.3089	.3918	.4680	.5293	.5822	.6253
170	.0308	.0633	.0985	.1352	.2136	.2925	.3720	.4447	.5070	.5587	.6025
180	.0301	.0616	.0954	.1303	.2050	.2805	.3553	.4252	.4867	.5377	.5820
190	.0294	.0601	.0925	.1259	.1972	.2693	.3407	.4070	.4677	.5185	.5628
200	.0288	.0586	.0898	.1220	.1900	.2591	.3271	.3907	.4491	.5006	.5443
210	.0281	.0571	.0873	.1184	.1839	.2497	.3149	.3757	.4327	.4830	.5269
220	.0275	.0556	.0851	.1151	.1780	.2411	.3033	.3621	.4172	.4673	.5107
230	.0269	.0542	.0829	.1120	.1726	.2333	.2927	.3494	.4030	.4517	.4956
240	.0263	.0529	.0808	.1092	.1675	.2260	.2831	.3380	.3896	.4370	.4810
250	.0257	.0518	.0788	.1065	.1629	.2192	.2743	.3274	.3773	.4237	.4672
260	.0252	.0507	.0770	.1040	.1586	.2130	.2663	.3179	.3660	.4111	.4540
270	.0246	.0496	.0752	.1017	.1546	.2073	.2588	.3089	.3554	.3994	.4414
280	.0242	.0486	.0736	.0994	.1507	.2020	.2518	.3003	.3455	.3886	.4293
290	.0237	.0477	.0721	.0972	.1470	.1970	.2450	.2925	.3364	.3786	.4178
300	.0233	.0468	.0707	.0951	.1434	.1923	.2388	.2850	.3279	.3691	.4072
310	.0229	.0459	.0693	.0930	.1402	.1879	.2330	.2781	.3200	.3600	.3975
320	.0225	.0451	.0679	.0910	.1372	.1837	.2276	.2716	.3127	.3514	.3885
330	.0221	.0443	.0667	.0892	.1344	.1798	.2226	.2653	.3057	.3433	.3800

TABLE 2 *(Continued)*

Density CO_2 in g/cc
Pressure in Bars

T°C.	500	600	700	800	900	1000	1100	1200	1300	1400
0	1.1024	1.1227	1.1405	1.1569	1.1698	1.1841	1.1990	1.2101	1.2211	1.2305
10	1.0759	1.0974	1.1167	1.1340	1.1485	1.1636	1.1788	1.1908	1.2022	1.2127
20	1.0482	1.0719	1.0928	1.1112	1.1272	1.1431	1.1586	1.1716	1.1835	1.1949
30	1.0200	1.0462	1.0689	1.0885	1.1060	1.1226	1.1386	1.1525	1.1650	1.1772
40	.9916	1.0204	1.0450	1.0659	1.0848	1.1022	1.1187	1.1335	1.1466	1.1595
50	.9630	.9945	1.0211	1.0434	1.0637	1.0819	1.0990	1.1146	1.1284	1.1419
60	.9340	.9686	.9973	1.0210	1.0427	1.0617	1.0795	1.0958	1.1104	1.1244
70	.9050	.9427	.9735	.9988	1.0218	1.0417	1.0603	1.0772	1.0926	1.1071
80	.8763	.9168	.9498	.9769	1.0010	1.0219	1.0413	1.0589	1.0750	1.0900
90	.8478	.8911	.9262	.9552	.9804	1.0023	1.0225	1.0409	1.0576	1.0731
100	.8195	.8655	.9038	.9337	.9600	.9830	1.0041	1.0231	1.0405	1.0565
110	.7915	.8402	.8797	.9125	.9398	.9639	.9860	1.0056	1.0236	1.0403
120	.7641	.8159	.8570	.8916	.9199	.9452	.9683	.9884	1.0070	1.0244
130	.7380	.7922	.8347	.8710	.9003	.9268	.9509	.9715	.9907	1.0087
140	.7132	.7693	.8134	.8507	.8812	.9087	.9338	.9549	.9747	.9933
150	.6889	.7469	.7928	.8309	.8628	.8912	.9171	.9386	.9590	.9781
160	.6650	.7255	.7727	.8117	.8450	.8742	.9008	.9228	.9436	.9631
170	.6424	.7051	.7533	.7933	.8277	.8577	.8848	.9074	.9287	.9488
180	.6211	.6853	.7347	.7755	.8109	.8417	.8692	.8924	.9141	.9347
190	.6014	.6665	.7169	.7585	.7947	.8262	.8539	.8777	.8999	.9208
200	.5833	.6485	.6998	.7423	.7789	.8111	.8391	.8634	.8860	.9072
210	.5658	.6315	.6834	.7266	.7636	.7964	.8246	.8495	.8725	.8939
220	.5497	.6153	.6675	.7113	.7486	.7821	.8105	.8359	.8594	.8809
230	.5347	.5998	.6525	.6965	.7341	.7680	.7969	.8226	.8465	.8683
240	.5203	.5850	.6381	.6823	.7200	.7544	.7836	.8097	.8340	.8560
250	.5064	.5709	.6244	.6687	.7065	.7411	.7707	.7971	.8217	.8441
260	.4929	.5573	.6111	.6556	.6935	.7282	.7582	.7849	.8098	.8326
270	.4798	.5443	.5983	.6430	.6810	.7157	.7460	.7730	.7982	.8213
280	.4673	.5320	.5859	.6307	.6688	.7036	.7342	.7613	.7869	.8103
290	.4556	.5202	.5740	.6190	.6570	.6918	.7227	.7500	.7758	.7995
300	.4444	.5088	.5626	.6076	.6457	.6805	.7115	.7390	.7651	.7890
310	.4338	.4978	.5517	.5966	.6347	.6695	.7007	.7282	.7547	.7787
320	.4238	.4873	.5412	.5860	.6241	.6589	.6902	.7178	.7445	.7686
330	.4143	.4772	.5310	.5757	.6139	.6486	.6800	.7077	.7346	.7588

TABLE 2 *(Continued)*

Density CO_2 in g/cc

Pressure in Bars

T°C.	25	50	75	100	150	200	250	300	350	400	450
340	.0217	.0435	.0655	.0874	.1318	.1761	.2131	.2595	.2991	.3357	.3716
350	.0213	.0427	.0643	.0857	.1292	.1725	.2137	.2540	.2928	.3284	.3637
360	.0210	.0420	.0631	.0842	.1268	.1690	.2095	.2489	.2867	.3214	.3561
370	.0206	.0413	.0620	.0828	.1245	.1657	.2053	.2440	.2809	.3150	.3488
380	.0203	.0406	.0610	.0814	.1222	.1625	.2015	.2394	.2754	.3090	.3420
390	.0200	.0400	.0600	.0801	.1201	.1594	.1978	.2350	.2701	.3033	.3355
400	.0197	.0393	.0591	.0788	.1178	.1565	.1942	.2308	.2650	.2979	.3293
410	.0194	.0387	.0582	.0774	.1158	.1538	.1909	.2267	.2603	.2928	.3233
420	.0191	.0382	.0573	.0761	.1139	.1512	.1876	.2227	.2557	.2878	.3172
430	.0188	.0376	.0564	.0749	.1121	.1487	.1845	.2189	.2513	.2830	.3117
440	.0185	.0370	.0556	.0737	.1103	.1464	.1815	.2152	.2471	.2784	.3065
450	.0183	.0365	.0547	.0726	.1086	.1441	.1786	.2117	.2431	.2738	.3019
460	.0180	.0360	.0539	.0715	.1070	.1419	.1758	.2083	.2393	.2695	.2974
470	.0178	.0355	.0531	.0705	.1054	.1396	.1732	.2050	.2356	.2652	.2929
480	.0175	.0350	.0524	.0695	.1038	.1374	.1706	.2020	.2320	.2612	.2886
490	.0173	.0345	.0516	.0686	.1023	.1351	.1682	.1991	.2286	.2573	.2843
500	.0171	.0340	.0509	.0677	.1009	.1339	.1658	.1962	.2253	.2536	.2802
510	.0168	.0336	.0502	.0669	.0995	.1319	.1634	.1934	.2202	.2501	.2762
520	.0166	.0331	.0496	.0661	.0982	.1301	.1611	.1907	.2191	.2467	.2724
530	.0164	.0327	.0489	.0652	.0970	.1284	.1589	.1882	.2161	.2434	.2686
540	.0162	.0323	.0483	.0644	.0957	.1267	.1567	.1857	.2132	.2401	.2650
550	.0160	.0319	.0477	.0635	.0945	.1250	.1546	.1833	.2104	.2370	.2614
560	.0158	.0315	.0471	.0628	.0933	.1234	.1526	.1809	.2077	.2339	.2580
570	.0157	.0311	.0465	.0619	.0921	.1219	.1506	.1786	.2051	.2310	.2548
580	.0155	.0308	.0460	.0612	.0909	.1194	.1487	.1763	.2026	.2282	.2517
590	.0153	.0304	.0454	.0604	.0898	.1189	.1468	.1742	.2002	.2254	.2487
600	.0151	.0301	.0449	.0597	.0887	.1174	.1450	.1722	.1979	.2227	.2457
610	.0149	.0297	.0444	.0590	.0876	.1160	.1433	.1702	.1957	.2201	.2428
620	.0148	.0294	.0439	.0583	.0866	.1146	.1416	.1682	.1935	.2175	.2400
630	.0146	.0291	.0434	.0576	.0856	.1133	.1399	.1663	.1914	.2150	.2373
640	.0144	.0287	.0429	.0570	.0847	.1120	.1383	.1644	.1893	.2126	.2346
650	.0143	.0284	.0424	.0563	.0837	.1107	.1368	.1626	.1872	.2102	.2321
660	.0141	.0281	.0419	.0557	.0828	.1095	.1352	.1608	.1852	.2078	.2297
670	.0139	.0278	.0415	.0551	.0819	.1084	.1337	.1590	.1832	.2055	.2273

TABLE 2 *(Continued)*

Density CO_2 in g/cc

Pressure in Bars

T°C.	500	600	700	800	900	1000	1100	1200	1300	1400
340	.4053	.4676	.5212	.5658	.6040	.6387	.6702	.6979	.7249	.7493
350	.3967	.4583	.5117	.5563	.5945	.6291	.6607	.6884	.7155	.7400
360	.3885	.4494	.5025	.5470	.5853	.6199	.6515	.6792	.7063	.7310
370	.3809	.4409	.4935	.5381	.5764	.6110	.6425	.6702	.6974	.7222
380	.3736	.4327	.4848	.5295	.5678	.6024	.6338	.6615	.6887	.7135
390	.3667	.4248	.4765	.5211	.5595	.5940	.6254	.6531	.6803	.7051
400	.3601	.4172	.4684	.5130	.5514	.5859	.6173	.6450	.6722	.6969
410	.3538	.4099	.4605	.5051	.5436	.5780	.6094	.6372	.6643	.6889
420	.3478	.4029	.4530	.4974	.5361	.5703	.6017	.6296	.6566	.6811
430	.3420	.3963	.4459	.4900	.5288	.5629	.5942	.6222	.6492	.6735
440	.3364	.3900	.4391	.4828	.5217	.5557	.5869	.6151	.6420	.6662
450	.3311	.3840	.4325	.4758	.5147	.5487	.5798	.6081	.6350	.6591
460	.3259	.3782	.4260	.4690	.5079	.5419	.5729	.6013	.6281	.6522
470	.3209	.3725	.4197	.4624	.5013	.5353	.5662	.5947	.6214	.6455
480	.3161	.3670	.4136	.4560	.4949	.5289	.5596	.5882	.6148	.6390
490	.3114	.3617	.4077	.4498	.4886	.5226	.5532	.5819	.6084	.6326
500	.3068	.3565	.4020	.4438	.4824	.5165	.5470	.5757	.6021	.6264
510	.3024	.3515	.3965	.4381	.4764	.5105	.5409	.5696	.5959	.6204
520	.2982	.3468	.3913	.4325	.4705	.5046	.5350	.5637	.5899	.6145
530	.2942	.3422	.3863	.4271	.4648	.4988	.5293	.5579	.5841	.6087
540	.2903	.3378	.3815	.4218	.4593	.4932	.5237	.5522	.5784	.6031
550	.2866	.3335	.3768	.4167	.4539	.4877	.5182	.5467	.5728	.5975
560	.2830	.3293	.3723	.4117	.4487	.4823	.5129	.5413	.5673	.5921
570	.2795	.3253	.3679	.4068	.4436	.4770	.5077	.5360	.5620	.5868
580	.2761	.3214	.3636	.4021	.4386	.4719	.5027	.5308	.5568	.5816
590	.2726	.3176	.3594	.3976	.4337	.4669	.4978	.5257	.5517	.5765
600	.2693	.3139	.3553	.3932	.4289	.4620	.4929	.5208	.5467	.5715
610	.2661	.3103	.3513	.3889	.4242	.4572	.4881	.5160	.5418	.5666
620	.2630	.3068	.3474	.3847	.4196	.4525	.4834	.5113	.5370	.5618
630	.2601	.3034	.3437	.3806	.4151	.4479	.4788	.5067	.5323	.5570
640	.2573	.3001	.3401	.3767	.4108	.4435	.4743	.5022	.5277	.5523
650	.2546	.2969	.3366	.3729	.4066	.4392	.4699	.4978	.5232	.5477
660	.2520	.2938	.3331	.3692	.4026	.4350	.4655	.4935	.5187	.5432
670	.2494	.2907	.3297	.3656	.3987	.4309	.4612	.4893	.5144	.5388

TABLE 2 *(Continued)*

Density CO_2 in g/cc

Pressure in Bars

T°C.	25	50	75	100	150	200	250	300	350	400	450
680	.0138	.0275	.0411	.0545	.0810	.1072	.1323	.1572	.1813	.2033	.2250
690	.0136	.0272	.0407	.0540	.0802	.1060	.1309	.1555	.1794	.2012	.2227
700	.0135	.0269	.0402	.0534	.0794	.1048	.1296	.1538	.1767	.1992	.2205
710	.0133	.0266	.0398	.0529	.0786	.1037	.1283	.1521	.1749	.1972	.2184
720	.0132	.0263	.0394	.0523	.0778	.1026	.1271	.1505	.1732	.1952	.2163
730	.0131	.0261	.0390	.0518	.0770	.1015	.1258	.1489	.1715	.1933	.2142
740	.0130	.0259	.0386	.0513	.0762	.1005	.1246	.1474	.1698	.1914	.2121
750	.0128	.0256	.0382	.0508	.0754	.0995	.1233	.1460	.1682	.1895	.2101
760	.0127	.0253	.0378	.0503	.0746	.0985	.1221	.1445	.1666	.1876	.2082
770	.0126	.0251	.0374	.0498	.0739	.0975	.1208	.1431	.1649	.1858	.2063
780	.0125	.0249	.0371	.0493	.0732	.0966	.1195	.1418	.1634	.1840	.2044
790	.0124	.0246	.0367	.0488	.0725	.0957	.1184	.1404	.1618	.1823	.2026
800	.0122	.0244	.0364	.0484	.0718	.0948	.1173	.1391	.1603	.1806	.2009
810	.0121	.0242	.0360	.0479	.0712	.0939	.1163	.1378	.1598	.1790	.1992
820	.0120	.0239	.0357	.0475	.0705	.0931	.1153	.1365	.1574	.1774	.1974
830	.0119	.0237	.0354	.0471	.0698	.0922	.1143	.1352	.1560	.1759	.1957
840	.0118	.0235	.0351	.0466	.0693	.0914	.1133	.1340	.1546	.1744	.1940
850	.0117	.0233	.0348	.0462	.0686	.0906	.1123	.1328	.1532	.1729	.1924
860	.0116	.0231	.0345	.0458	.0680	.0898	.1113	.1316	.1519	.1714	.1907
870	.0115	.0228	.0342	.0454	.0674	.0890	.1103	.1305	.1506	.1700	.1891
880	.0114	.0226	.0339	.0450	.0669	.0883	.1093	.1294	.1493	.1685	.1874
890	.0113	.0224	.0336	.0446	.0663	.0875	.1083	.1283	.1481	.1671	.1858
900	.0112	.0223	.0333	.0442	.0657	.0868	.1073	.1272	.1468	.1657	.1841
910	.0111	.0221	.0330	.0438	.0652	.0861	.1064	.1261	.1455	.1642	.1825
920	.0110	.0219	.0327	.0434	.0646	.0854	.1054	.1251	.1442	.1629	.1810
930	.0109	.0217	.0324	.0429	.0641	.0846	.1044	.1241	.1429	.1615	.1794
940	.0108	.0215	.0322	.0425	.0635	.0839	.1035	.1231	.1416	.1602	.1779
950	.0107	.0213	.0319	.0422	.0630	.0832	.1026	.1222	.1404	.1589	.1764
960	.0106	.0211	.0317	.0419	.0624	.0825	.1018	.1212	.1392	.1577	.1750
970	.0106	.0209	.0315	.0415	.0619	.0817	.1009	.1203	.1380	.1564	.1736
980	.0105	.0208	.0312	.0412	.0614	.0810	.1001	.1193	.1370	.1552	.1723
990	.0104	.0207	.0309	.0409	.0609	.0804	.0993	.1184	.1360	.1540	.1710
1000	.0103	.0205	.0307	.0407	.0604	.0797	.0986	.1174	.1350	.1527	.1697

TABLE 2 *(Continued)*

Density CO_2 in g/cc

Pressure in Bars

T°C.	500	600	700	800	900	1000	1100	1200	1300	1400
680	.2469	.2877	.3264	.3621	.3949	.4269	.4570	.4851	.5102	.5345
690	.2444	.2848	.3232	.3587	.3912	.4230	.4529	.4810	.5060	.5303
700	.2420	.2819	.3201	.3553	.3876	.4192	.4489	.4770	.5019	.5262
710	.2396	.2791	.3170	.3520	.3841	.4155	.4450	.4730	.4979	.5221
720	.2372	.2764	.3140	.3487	.3807	.4119	.4411	.4691	.4940	.5181
730	.2349	.2737	.3110	.3455	.3774	.4084	.4374	.4653	.4901	.5142
740	.2326	.2711	.3081	.3424	.3742	.4049	.4337	.4615	.4863	.5104
750	.2303	.2685	.3052	.3393	.3711	.4015	.4301	.4578	.4826	.5066
760	.2281	.2660	.3024	.3363	.3680	.3982	.4266	.4542	.4790	.5029
770	.2259	.2636	.2996	.3334	.3649	.3949	.4232	.4506	.4754	.4993
780	.2238	.2613	.2969	.3305	.3619	.3917	.4199	.4471	.4719	.4957
790	.2217	.2590	.2942	.3277	.3589	.3886	.4166	.4437	.4685	.4922
800	.2197	.2567	.2916	.3249	.3560	.3856	.4134	.4403	.4651	.4888
810	.2178	.2545	.2890	.3222	.3531	.3826	.4102	.4370	.4618	.4854
820	.2159	.2523	.2865	.3195	.3503	.3796	.4071	.4338	.4585	.4821
830	.2141	.2502	.2841	.3169	.3475	.3767	.4041	.4306	.4553	.4788
840	.2123	.2481	.2818	.3143	.3448	.3738	.4011	.4275	.4522	.4756
850	.2105	.2461	.2796	.3118	.3422	.3710	.3981	.4245	.4491	.4724
860	.2088	.2441	.2774	.3093	.3396	.3683	.3952	.4215	.4461	.4693
870	.2071	.2422	.2752	.3069	.3370	.3656	.3923	.4186	.4431	.4662
880	.2054	.2403	.2731	.3045	.3345	.3630	.3895	.4157	.4402	.4632
890	.2037	.2384	.2710	.3022	.3320	.3604	.3868	.4129	.4373	.4602
900	.2020	.2365	.2689	.2999	.3296	.3579	.3841	.4102	.4345	.4573
910	.2004	.2346	.2669	.2977	.3272	.3554	.3815	.4075	.4317	.4544
920	.1988	.2328	.2649	.2955	.3248	.3529	.3790	.4048	.4289	.4516
930	.1972	.2310	.2630	.2934	.3225	.3505	.3765	.4022	.4262	.4488
940	.1956	.2293	.2611	.2913	.3202	.3481	.3741	.3996	.4235	.4461
950	.1941	.2276	.2592	.2893	.3180	.3458	.3717	.3971	.4208	.4434
960	.1926	.2259	.2574	.2873	.3159	.3435	.3694	.3946	.4182	.4408
970	.1911	.2242	.2556	.2853	.3138	.3412	.3671	.3921	.4156	.4382
980	.1896	.2226	.2538	.2834	.3118	.3390	.3648	.3897	.4130	.4356
990	.1882	.2210	.2520	.2815	.3098	.3368	.3625	.3873	.4104	.4330
1000	.1868	.2194	.2503	.2796	.3079	.3346	.3603	.3850	.4078	.4305

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SOME PROBLEMS OF ALLUVIAL TERRACE MAPPING*

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ABSTRACT.—Alluvial terraces have been studied intensively during recent years in the central plains region of the United States. They have been mapped in many valleys, particularly in conjunction with ground-water and engineering studies being made by the State Geological Surveys and the United States Geological Survey. In many places the alluvial terraces have been mapped by surface form but interpreted in terms of underlying materials. The purpose of this discussion is to list and describe briefly some of the situations, including false scarps, flanking pediments, loess or colluvial veneers, and dissected old terrace surfaces, that may lead to incorrect mapping and interpretation of valley history when terrace form only is examined.

INTRODUCTION

Alluvial terraces are those surfaces, now standing distinctly above adjacent flood plains, that were produced by dissection of earlier valley flats. During the past 15 to 20 years the accelerated programs of ground-water investigations by Federal and State Geological Surveys, initiation of construction-materials studies by the Engineering Geology Branch of the Federal Survey, increasing emphasis on Pleistocene geology by the State surveys, and studies of vertebrate paleontology and anthropology by State universities and museums have resulted in increasingly intensive study of alluvial river terraces in the central plains region, particularly in Kansas and Nebraska. In these states general reports have recently reviewed the sequence, age, and correlation of alluvial river terraces (Condra and Reed, 1950; Schultz, Lueninghoener, and Frankforter, 1951; Frye and Leonard, 1952).

Terrace studies in this region are concerned primarily with the deposits underlying the terrace surface, but the terrace form has been used in many cases for correlation and mapping—thus mixing physiography and stratigraphy (Leonard and Frye, 1951). Many problems arise in mapping of terraces in relatively minor valleys and across a region in which average rainfall ranges from 15 to 40 inches. Correlation in some cases has been facilitated by the fossil mollusks and petrographically distinctive volcanic ash contained in the terrace deposits, but areal mapping continues to be based primarily on surface form.

Terraces have been described and mapped in many regions throughout the world, and are described in textbooks on physical geology, geomorphology, and physiography. In 1944 Johnson presented a review of the problems of terrace correlation. With such a wealth of terrace literature further discussion of the subject may seem superfluous. Much of the existing literature deals, however, with coastal or marine terraces and with the *form* of river terraces whereas terrace mapping in Kansas uses the terrace form as a tool for mapping *deposits*. It is the deposits that are of prime importance in problems of water supply, construction materials, or engineering, and they contain the fossils or artifacts. Thus a technique of the geomorphologist becomes a tool of stratigraphic correlation and areal mapping. The purpose of this discussion is to list and describe briefly some of the situations that may lead to an

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incorrect mapping of deposits and incorrect interpretation of valley history when terrace form alone is used as the basis of alluvial terrace mapping. All illustrations used are drawn from valleys in Kansas but many of the types of problems illustrated have application far beyond the Great Plains region.

RECOGNITION OF TERRACE SEQUENCE

Clearly, in any mapping problem the first decision concerns the units to be mapped. Even though terraces cut in bedrock—in spite of well-developed terrace form—are ignored, there still remains the question of which alluvially floored surfaces should be distinguished. As described repeatedly in physiographic literature (Davis, 1889, 1909; von Engeln, 1942, p. 238-239), streams slowly incising their valleys while swinging laterally may leave remnants of alluvially floored terrace surfaces at any or all vertical positions between the floodplain and the highest alluviated surface. Such terrace remnants have been called "unpaired," and as each such terrace segment is controlled by the local history of stream-channel planation they are incapable of correlation along a valley. Therefore, when alluvial terraces are being mapped as an adjunct to stratigraphic work, such unpaired terraces should not be designated as distinct entities, or chaos will result.

It is, rather, the purpose of areal geologic mapping to use as cartographic units deposits that possess, from one place to another, at least a fair degree of physical uniformity, similar genesis, and at least rough contemporaneity. These requirements are usually met by "paired" alluvial terraces—that is, terrace remnants flanking the stream valley on both sides at similar elevations. During Pleistocene time many of the valleys of the Midwest region were filled and entrenched repeatedly. In valleys where the amount of valley trenching exceeded the depth of the next succeeding valley fill the series of terrace remnants now existing may be correlated, and from them the history of cut and fill in the valley may be reconstructed (Leonard, 1952). In fact, the deposits underlying such a terrace surface commonly possess many if not all the requirements for a stratigraphic formation, including regional similarity of lithology, mappability, and approximate regional contemporaneity.

FALSE GAIN OR LOSS OF A TERRACE

The worst error made in terrace mapping is the delineation of a false alluvial unit that in fact does not exist, or the failure to recognize one that does exist. Such errors are easy to make. Figure 1 shows three idealized situations conducive to this type of error.

In figure 1A two terrace forms, each possessing a distinct scarp, occur along a valley side, where a thick alluvial fill underlies the original terrace surface and resistant bedrock forms the floor of the alluvial fill. If the alluvial fill is eroded more rapidly than the resistant bedrock, two "step" forms may appear in the topography. Such a false double terrace developed in 75 feet of Kansan and Illinoian alluvium on Cretaceous Dakota formation occurs along part of Smoky Hill River Valley in Ellsworth and Russell Counties in central Kansas. Where resistant lenticular sandstone beds underlie the Pleistocene deposits two terraces appear in the topography—one on the surface of

the Pleistocene fill and the other on the Cretaceous sandstone at the base of the fill (Frye, Leonard, and Hibbard, 1943).

An illusion of two terraces where only one alluvial terrace occurs may also be given by the presence of colluvial, landslide, or mudflow deposits on an alluvial terrace surface (fig. 1B). Although such a condition is not prom-

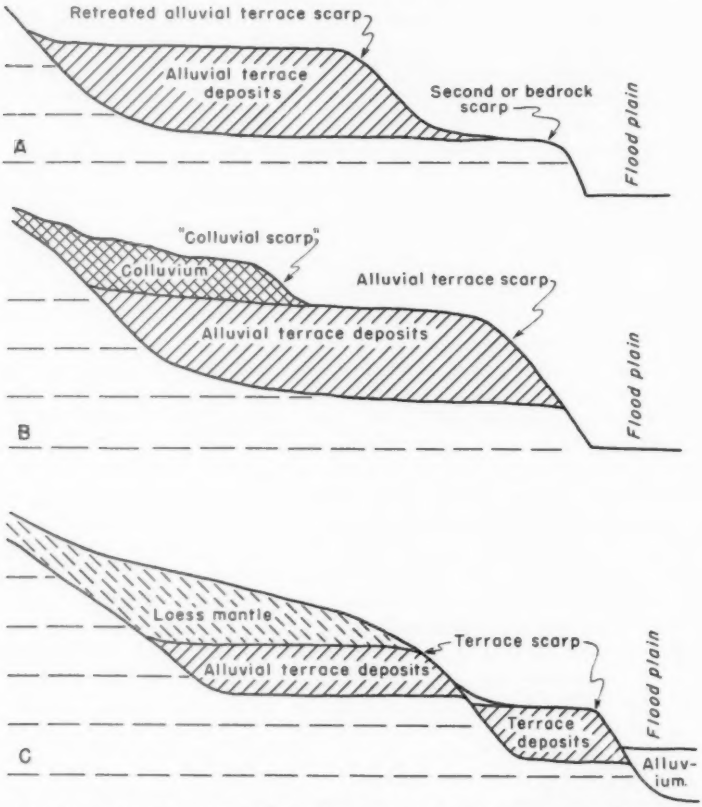

Fig. 1. Idealized sections showing false gain or loss of a terrace. A, Double terrace form produced by more rapid erosion of alluvial deposits than of resistant underlying bedrock. B, Double terrace form produced by secondary scarp on edge of younger overlying colluvium. C, Second terrace form masked by deposit of younger loess.

inently displayed along the major valleys of the Great Plains region, it is found at many places in the small tributary valleys, particularly in the more humid eastern part, as in eastern Kansas.

Older alluvial terraces along many valleys in northwestern Kansas are obscured by loess deposited to various depths on the valley side and on the terrace surface as shown in the generalized section in figure 1C. Such a

condition is exceptionally well developed along Prairie Dog Creek Valley throughout its extent across Norton County, Kansas (Frye and Leonard, 1949). Here, two well-preserved alluvial terraces flank the valley almost continuously along its 35-mile course across the county. The surface of the younger (Almena) terrace was formed during late Wisconsinan and is virtually free of loess. The higher terrace is underlain by Illinoian stream deposits which contain at the top the buried Sangamon soil. Thick deposits of early Wisconsinan Peoria loess extend from the valley slopes over the surface of the Illinoian alluvial terrace. The loess blanket is not of uniform thickness, and as the thickness is at least in part controlled by the topography on which it was deposited, thick accumulations occur over the terrace-valley wall angle, thus effectively obscuring the lateral limit of the terrace surface except in deep gullies or in bore holes.

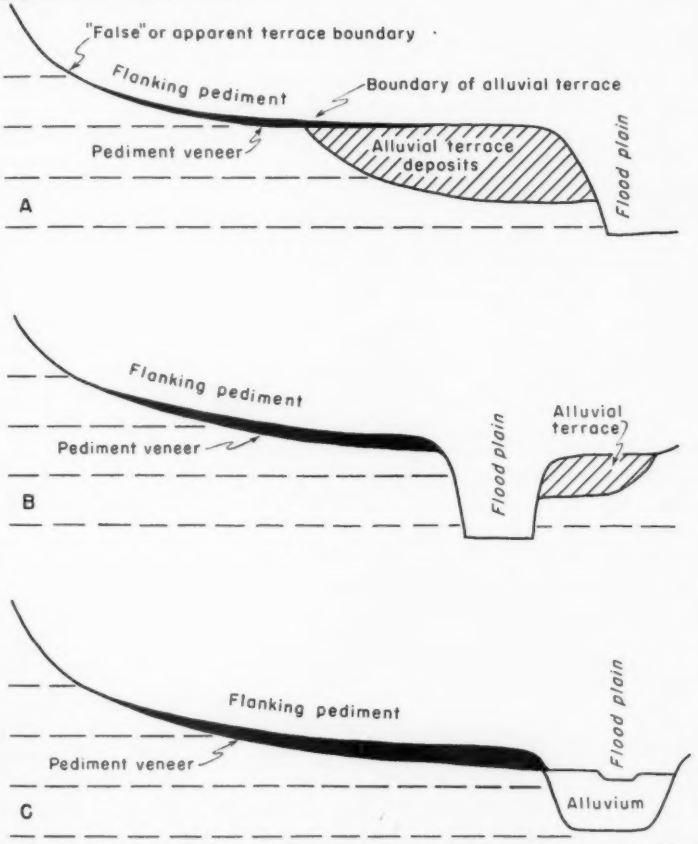

Fig. 2. Effect of flanking pediments on the alluvial terrace form. A, Flanking pediment graded to surface of alluvial terrace obscuring lateral limit of alluvial terrace. B, Flanking pediment graded to former position of alluvial terrace. C, Veneer on flanking pediment surface giving false impression of low terrace.

THE PROBLEM OF THE FLANKING PEDIMENT

The concept of pediments has been in geologic literature for many years. In the thinking of many geologists, however, the term pediment has been associated only with mountain fronts in a desert environment, partly at least because geologists generally have not sought such forms in the topography of the semiarid to subhumid Great Plains region.

Erosion surfaces thinly veneered with clastic debris and displaying a typical pediment form are marginal to many valleys in the Great Plains. Such features have recently been described and called "flanking pediments" (Frye and Leonard, 1952, p. 25) from their position flanking the stream courses to which they are graded. Flanking pediments should not, of course, be confused with alluvial terraces or mapped with them, but since in their streamward part they approach the horizontal and are commonly veneered with clastic materials, such confusion on the part of the field geologist is understandable. This possible confusion is even more likely in the case of valleys where alluvial terraces occur at several heights above the channel and each such terrace has a flanking pediment graded to it.

Three idealized sections showing situations where flanking pediments present problems in field mapping are presented in figure 2. In the first of these (fig. 2A) a flanking pediment surface is shown graded to a former floodplain surface, now dissected and standing above the channel as an alluvial terrace. Clearly, the marginal (alluvial) part of such a surface is properly mapped as an alluvial terrace, but likewise one can see that the lateral extension of the surface should not be mapped as such a terrace. This problem is particularly well represented along the central Smoky Hill River Valley in Ellis and Trego Counties, Kansas, where Alvin R. Leonard and D. W. Berry have mapped such surfaces in conjunction with ground-water studies. Where mapping is being done as a background for ground-water evaluations, a terrace symbol on a map must reflect at least to some degree the deposits under the terrace surface. But if the topographic "break" were mapped by surface observation only, the terrace symbol would not reflect the deposits, and therefore it is necessary to call upon subsurface data to determine the lateral extent of the *alluvial* terrace.

A somewhat different situation is shown in figure 2B where a part of the flanking pediment graded to a former position of the floodplain is now isolated from a segment of alluvial terrace by the trench of the modern valley and gives a false impression that matched terrace segments exist. This situation is also well illustrated in the Smoky Hill and Solomon River Valleys of central and western Kansas.

Another type of confusion in the study of terraces is shown in figure 2C, an idealized section typical of some segments of the Cimarron River Valley in southwestern Kansas (Frye and Smith, 1942). Here a broad and virtually undissected flanking pediment surface is graded to a narrow floodplain. The sheet of debris that veneers the low-angle surface is sharply terminated at the edge of the active floodplain and gives the illusion in the topography of a very low alluvial terrace.

EFFECT OF RESISTANT BEDROCK LAYER

The projection of a terrace gradient and the measurement of vertical intervals between terrace surfaces or between terrace surface and floodplain are two commonly used techniques of terrace correlation. In the Great Plains region the thickness of many bedrock units is measured in hundreds of feet and there is strong contrast between adjacent units in their resistance to erosion. Such a bedrock situation in an area where stream incision has been rapid makes these techniques precarious.

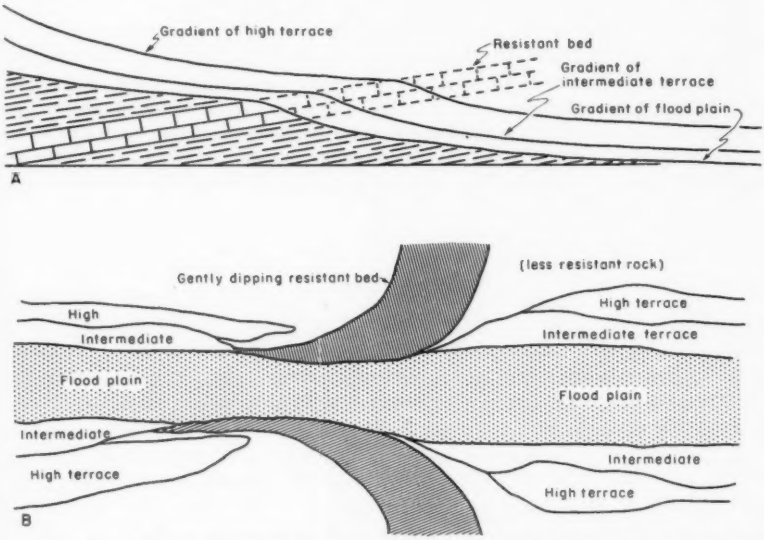

Fig. 3. A, Effect on terrace profile of a resistant bed in the bedrock. This illustrates the danger of making terrace correlations by simple determination of height of terrace surface above floodplain. B, Effect of resistant bed in the bedrock on map of alluvial terraces.

The schematic cross section and map shown in figure 3 illustrate the distortion of profile and the discrepancies of vertical interval that may be produced in alluvial terraces by alternating resistances of thick bedrock units. Such conditions occur along several valleys in central Kansas where streams cross the belt of Cretaceous rocks, including the Carlile shale and the Fort Hays limestone member and Smoky Hill chalky shale member of the Niobrara formation (Leonard, 1952). The Fort Hays limestone is much more resistant than the thick shales above and below and therefore it modifies the gradient of the floodplain where it crosses this limestone and constricts the width of floodplain. In parts of the region where the bedrock units are thin, or where all parts of the bedrock present approximately uniform resistance to erosion, this problem is not encountered.

PROBLEMS OF CORRELATION BY ALTITUDE MATCHING

Johnson (1944) has discussed in detail many of the problems and pitfalls encountered in attempts to correlate terraces primarily by determining surface altitudes and projecting these altitude measurements into a pattern. Therefore only two problems commonly encountered in the Great Plains region will be discussed here. These two are represented by schematic sections in figure 4.

The first and more important problem, illustrated by figure 4A and 4B, is that of a relatively even or uniform channelward slope on the terrace surface. The discrepancies in altitude of terrace surface between the bedrock valley wall and the crest of the terrace scarp at the edge of the floodplain may equal or even exceed the actual height of the terrace surface above the floodplain. Such strong discrepancies are commonly produced by a combination of two processes—sheet erosion near the scarp and deposition on the terrace surface near the valley wall. Deposition on the terrace surface near the valley wall is more common in the low-rainfall belts of the Great Plains, where the minor tributaries entering the valley are incompetent to incise their channels

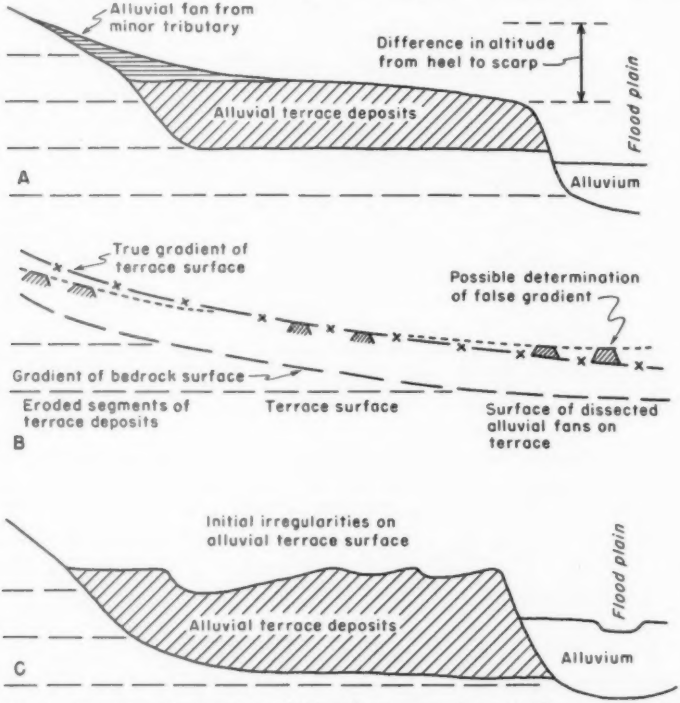

Fig. 4. Elevation discrepancies of alluvial terrace surfaces. A, Terrace where alluvial fan has given super-elevation near valley wall and sheet erosion has lowered the surface near the scarp. B, False terrace profile plotted by use of unreliable elevation data. C, Initial (depositional) irregularities on an alluvial terrace surface.

below the terrace surface. The loss of transporting power where the small stream encounters the relatively flat terrace surface causes the stream to drop the sediment load it has acquired in the steeper headwaters area and thus build an alluvial fan. The waters of the small tributary are no longer restricted to a single confined channel and either infiltrate downward into the relatively permeable materials of the terrace fill or flow over its surface as sheet wash to the terrace scarp.

Although this type of modification of terrace surfaces is more common in central and western Kansas, it has been observed, developed to a lesser degree, in the Kansas River Valley in the extreme eastern part of the State. A possible effect on the determination of terrace gradient is illustrated in figure 4B.

Figure 4C illustrates the divergent altitude determinations that may be obtained on a young and unmodified alluvial surface. Where such a surface is undissected and fully observable it scarcely constitutes a problem as the significance of the irregularities should be obvious to any field geologist. However, where such a surface has been dissected and measurements are made on isolated remnants, the cause of the discrepancies in altitude may be less obvious.

DISSECTED HIGH-LEVEL TERRACES

Alluvial terrace mapping attains its ultimate complexity perhaps, in areas of high-level terraces that have been dissected to a mature topography. A situation of this kind is well illustrated along the valley of Kansas River in the eastern part of Kansas where Davis and Carlson (1952) named and mapped the Menoken terrace. The Menoken is an outwash terrace of Kansan age; it stands 80 to 100 feet above the floodplain; the bedrock floor on which the alluvial deposit rests is 30 to 40 feet above the floodplain of Kansas River. The alluvial terrace deposits consisted originally of outwash or valley-train material from the Kansan glacier; the bedrock below the present floodplain has been incised about 150 feet below the reconstructed surface of this high terrace. Where the Menoken terrace is preserved it has been dissected to a rolling mature topography of moderately fine texture, and the present surface locally is thinly veneered with loess and colluvium. This feature is not a "terrace" in the sense of a clearly recognizable land form but rather an intermittent belt of hills intermediate in height between low terraces and upland. Although Kansan outwash or Meade formation constitutes the bulk of the deposits, much of the present surface is veneered with the younger Sanborn formation, and at some places Kansas till and the pro-Kansan Atchison formation are exposed, and therefore the mapping of these stratigraphic entities would result in meaningless cartographic confusion. In mapping such a feature as a unit we are truly merging land form with stratigraphy because we are using the criteria of both fields for the delineation of a single unit, and once it is mapped there is question as to whether it should be designated on the map as a stratigraphic or as a physiographic unit.

Mapping of dissected high-level early Pleistocene alluvial terraces has acquired considerable importance in the Midwest because of their importance

to ground-water studies. They have been studied along the valleys of Kansas River, Smoky Hill River (Frye, Leonard, and Hibbard, 1943), North Fork Solomon River (Leonard, 1952), Saline River (Berry, 1952), and several streams in east-central Kansas (Moore, Jewett, and O'Connor, 1951).

A less readily solved problem of the same general type exists in the Flint Hills section of east-central Kansas. Here (Frye and Leonard, 1952) chert stream gravels occur at many topographic positions and range in age well back into late Tertiary. In some places the superior resistance to erosion of these chert gravels has caused topographic inversion, and the gravels now locally cap divides as much as 300 feet above adjacent major flood plains. Although the lower and younger of these chert gravel deposits may properly be considered alluvial terraces, the highest deposits which by topographic inversion cap the local divides are not related to an existing terrace form. The consideration of appropriate designation of such deposits on a geologic map goes beyond the problem of alluvial terrace mapping.

CONCLUSIONS

Areal mapping in plains regions has emphasized the interdependence of land forms and deposits (or stratigraphy) in the study and delineation of alluvial terraces. A terrace, when considered from the aspect of surface form alone, is not properly included as an independent unit for areal geologic mapping. However, when geologic mapping is done as a basic part of studies of ground-water resources or engineering problems, alluvial terraces assume major importance because of the particular characteristics of the deposits that underlie their surfaces. The result is a hybridization of geomorphology and stratigraphy—the mapping of a surface form as an index to underlying materials. Where this practice is followed slavishly, the result is unsatisfactory because the surface form may not everywhere indicate similar subsurface conditions. In order to prevent misleading and inconsistent results the stratigraphy of the terrace deposits should be utilized in mapping, and the map unit should be the assemblage of deposits associated with a particular terrace level or cycle, the surface form being used only as one tool in mapping. In dealing with relatively undissected terrace surfaces, and particularly in regions where flanking pediments are well developed, subsurface data may be essential for recognition of extent of the deposits of an alluvial terrace.

The mapping of an *alluvial* terrace is in fact the mapping of a lithologic stratigraphic unit. The mapping of a *terrace*, or a flanking pediment surface, as a simple land form should be considered a problem of geomorphology and not included as a part of an areal geologic map.

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REVIEWS

Clay Mineralogy; by RALPH E. GRIM. P. xii, 384, 121 figs. New York, 1953 (McGraw-Hill Book Company, $9.00).—Present knowledge in clay mineralogy is set forth in this well-printed small treatise of 14 chapters with 121 figures and about 50 short tables. This is the fourth recent book on the general subject. It differs from the previous ones in being more comprehensive, but such coverage is attained by considerable sacrifice in depth of treatment which is countered by completeness of the reference list containing about 1000 citations.

The chapter headings in brief are: composition, classification, structure, X-ray diffraction, electron micrography, ion exchange, clay-water systems, heating curves, organic compounds, optical properties, and origin and occurrence of the clay minerals. The choice is first to give the historical background for the recognition and naming of the various minerals. Each is again treated in successive chapters on specific properties. This is an orderly procedure that makes for smooth reading. Discussions are usually descriptive rather than quantitative. This is a serious drawback in the treatment of cation exchange and to a lesser extent in thermal analyses. There is a tendency to be uncritical in presenting claims of authors which later developments have not supported. This is true in the treatment of the clay-water systems where much that has appeared in the literature is hypothetical.

The last 50 pages are devoted to origin and occurrence of the clay minerals, the geological and soil aspects of the subject. What has been said is briefly summarized with an awareness of the fact that, particularly with regard to sediments, "many of the determinations that have been made are incomplete or are based on inadequate analytical data." The mode of synthesis of the clay minerals is covered in this section. It is here that current progress is greatest and most likely to introduce need for revision of present concepts.

The book can be recommended less as a source of details of past findings about clay minerals than as a guide to the literature and as a summary of present concepts.

STERLING B. HENDRICKS

Conversation with the Earth: A Geologist's Autobiography; by HANS CLOOS. PP. 413, illus. New York, 1953 (Alfred A. Knopf, $5.75.)—The folds in rocks "turn about their axes like parts of machines." The traces of rotation "run about the axes like flutings and grooves, because the axle was not greased. . . ." With such turns of phrase a geologic structure is made to come alive by this perceptive geologist for whom quartz is the "cocky street-urchin of geological history, the indestructible mineral that dominates all weaker ones." The things the tourist views superficially this traveler observes with both scientific insight and artistic perception: the origin of the mud in an African river, the structure of the Rift Valley beneath the Red Sea, a volcanic cone in Java. The compact descriptions of landscapes and structures, their analytical dissection, and the lucid explanations of how they came to be and what they mean should seize the imagination of any student of nature.

To this reviewer the book belies its subtitle, for although it is most certainly a conversation with the Earth it is hardly an autobiography. Rather it is a group of geological essays on bits of the Earth's surface visited by

a passionate pilgrim—the diamond pipes of south Africa, the Namib Desert, the Oslofjord, the Yosemite, western Java, and many others. Some of the pieces are no more than impressions; others are constructed in almost meticulous detail. Unavoidably some liberties are taken in the way of overgeneralization, and passages here and there are overwritten. But the whole satisfyingly reveals a rare combination of skill in research, imaginative perception, and lucid writing. From it emerges a clear picture of a man who loves the Earth, is imbued with a deep and lasting desire to understand it, and is not at all preoccupied with himself and his own reactions. Hans Cloos was a distinguished geologist, but the reader ignorant of his professional reputation and accomplishments would sense this only through the ease and skill with which the material is presented. The first person singular is virtually absent; the geologist stands in the background while the Earth holds the center of the stage.

Many could envy Hans Cloos his life. It was rich and rewarding because he filled it with a never-ending inquiry that continually fascinated him. He admired his teachers and quite evidently loved to teach and loved his students as people. His was a pantheistic philosophy, for he saw in Nature a great and complex harmony, an equilibrium, and of that harmony he was himself a part.

This is not a great book (its author would have been the very last to assert the contrary) but it is deeply felt. Published originally in German, it has been well translated, and its geologic essays are enlivened by good photographs and by skillful pencil sketches such as those with which Cloos delighted his students and embellished some of his many professional papers.

RICHARD FOSTER FLINT

Arctic Bibliography; prepared under the direction of THE ARCTIC INSTITUTE OF NORTH AMERICA. 3 vols., 4478 pages. Washington, 1950: Department of Defense (U. S. Government Printing Office, $12.75).—Only a government agency or a wealthy foundation could afford to underwrite a work as monumental as this one. The 20,003 entries, each with a brief but comprehensive analysis, are the product of skilled bibliographers working in the Library of Congress and other libraries, over a period of several years. The titles are thoroughly indexed in a 1500-page index, so that the scientist or engineer in search of published material on the Arctic region can find it easily. The bibliography is currently available from the Superintendent of Public Documents, Washington.

RICHARD FOSTER FLINT

Seismic Prospecting for Oil; by C. HEWITT DIX. P. xx, 414; 175 figs. New York, 1952 (Harper and Brothers, $7.50).—Dr. Dix has written the first book devoted entirely to that aspect of the exploration sciences of dominant economic importance today: *Seismic Prospecting for Oil.* The book, concerned primarily with the interpretation of seismic data, is aimed at students, trainees, and especially geophysical operating personnel and exploration geologists desiring some knowledge of those aspects of seismic prospecting outside of their immediate spheres of contact. The author has assumed that the reader's background includes two years of college physics and mathe-

matics, but his treatment is largely elementary, and a reader who remembers some trigonometry, a bit of physics and, perhaps, the notation of the calculus should have no difficulty with most of the book.

The book is characterized by a large number of excellent diagrams, and in fact, at times gives the impression of having been written around the drawings. These illustrations are novel in that they include pertinent mathematical formulae and development. The publisher's blurb points out that purchasers of the book will be able to follow these developments even though they do not read English. This may be true, provided that the non-reader needs no captions or explanations of the symbols used. However, this presentation is a mixed blessing, and in deference to those purchasers who can read English, it would have been desirable to repeat the various mathematical relationships in the texts discussing them. Unless one is quite familiar with the relationship being developed (in which case one would likely not be a reader), following a discussion which refers to each step only by the number assigned it on a diagram, which may be two pages back, is at best annoying, and at worst, a considerable impediment to understanding.

Each of the five parts of the book is introduced with a short statement of content and a note as to the readership for whom the part is intended. The parts consist of a rather trivial introduction, an excellent section on computing methods, very good sections on interpretation for the reflection seismograph and on computation and interpretation of refraction work, and an interesting section on the initiation and propagation of seismic transients. An extensive bibliography (arranged alphabetically by author) and an adequate index are included.

It seems unfortunate that the author was unable to include, presumably to keep the book to a reasonable size, certain aspects of seismograph work that the interpreter usually finds necessary for non-routine work. The relation of the acoustic properties of the earth to its stratigraphy and structure, the relation of instrumental (electrical) output to acoustic input, the available means of operating on a seismic signal, and the theory of some of the more important field methods of improving records (multiple detectors, Poulter Seismic Method, multiple shot holes) are either omitted or treated in a very cursory manner. A possible criticism of the sections on computing, interpretation, and refraction concerns the chance that the reader completely unfamiliar with the subject will obtain the idea that the specific techniques presented are the only ones available or used. Excellent as these methods are, it would perhaps have been desirable to emphasize the existence of others.

Some geophysicists may express regret that Dr. Dix's notably strong theoretical background was not drawn upon more deeply. Although the author purposely chose not to produce an advanced theoretical treatise, it is the reviewer's opinion that even experienced interpreters will find much material of interest in the book. It is an important contribution to the literature, and is recommended to the readership for which it was intended.

L. V. LOMBARDI

Soil Microbiology; by SELMAN A. WAKSMAN. P. vii, 356; 130 figs., 77 tables. New York, 1952 (John Wiley & Sons, Inc., $6.00).—The preface to *Soil Microbiology* promises to present "a broad outline of the subject, one might even say a philosophy of soil microbiology" primarily for use as a text. One would expect, from the years of Professor Waksman's experience, a rewarding volume. As the preface puts it, the soil is "teeming with life" . . . which gives it the "characteristic properties that make it a suitable medium for plant and animal life." The variety and activity of the forms of life in the soil is a fascinating study in itself; the ecological importance of these activities makes soil microbiology a required subject for students of agriculture and animal husbandry as well as general microbiologists. And for these students the intellectual history of this science is as important as the facts it deals with. The history of soil microbiology has been well treated here, especially in the first chapter, illustrated with pictures of historically important investigators. Beijerinck looks characteristically crotchety, Thom as charming as those who have met him even briefly know him to be. These are the touches that make history alive to students.

Unfortunately, the book as a whole has a somewhat historical flavor. Less than half of the references in which "the student . . . can find up-to-date, concise statements concerning the problems discussed . . ." are to papers or books published since 1940. Such topics as "Humus: nature and formation," "Decomposition of soil organic matter and evolution of carbon dioxide," and "Transformation of mineral substances in soil by microörganisms" do not seem to have interested modern investigators; these chapters have no references to work published since 1940. A chapter on "Associative and antagonistic effects . . . ," dealing primarily with antibiotics, is a welcome exception.

The philosophy which Professor Waksman presents seems to be a version of that of Winogradsky: the physiology of the soil is developed in preference to that of the microörganisms within it. The reader gets the impression that not specific microörganisms, but the soil, decomposes substrates, evolves carbon dioxide, etc. This is a valid philosophy but a narrow one and one which is self-limiting, since to confine oneself to experimenting with tumblers of dirt, distrusting pure culture studies and elective culture techniques, is to be unable to control experimental variables so as to learn with precision what each member of the microbiota is capable of contributing to the tumbler of dirt or the field of corn.

Statements that the special characteristics of the protozoa include "protoplasm in a colloidal state," "the most important constituents of the [protozoan] cell are the complex proteins" seem trite and suggest hasty writing. So do the numerous errors of fact. One appreciates that it is impossible to write a text which does not contain one or more hideous errors, but the following are cited as examples chosen from too large a population: "A typical nucleic acid has the composition $C_{36}H_{48}O_{30}N_4P_4$ and is made up of . . . . a carbohydrate (hexose or pentose) . . . ," nitrogen fixers include "*Diplococcus pneumoniae, Aerobacter aerogenes.*" In general, the text does not seem to achieve the objectives for which it strove.

WOLF VISHNIAC
HELEN SIMPSON VISHNIAC

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